INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Rainfall threshold to trigger landslides in unsaturated soils: A laboratory model study

Étude par un modèle de laboratoire du seuil de précipitations déclenchant les glissements de terrain dans les sols non saturés

Mohammad Ahmadi-adli, Nejan Huvaj, Nabi Kartal Toker
Civil Engineering Department, Middle East Technical University, Turkey, nejan@metu.edu.tr

ABSTRACT: Rainfall triggered landslides are common natural hazards with significant consequences all over the world. In this study, laboratory model tests are conducted which aims to obtain the rainfall intensity-duration threshold to trigger landslides in a slope composed of unsaturated soil in a flume setup. Sixteen laboratory model tests are conducted to obtain the rainfall intensity-duration threshold. Some of the conclusions in this study are: (1) rainfall intensity-duration (I-D) thresholds that would trigger a landslide can be obtained physically in the laboratory, (2) the shape of the I-D threshold plot is demonstrated to be a partly-linear relation in log-log plot for the soil used in this study, (3) below a certain rainfall intensity (15 mm/hour in this study) landslides are not triggered in unsaturated soil used in this study, (4) it is observed that shallow landslides are not triggered by any rainfall when the soil is dense.

RÉSUMÉ: Les glissements de terrain provoqués par les précipitations sont des risques naturels courants ayant des conséquences importantes partout dans le monde. Dans cette étude, des essais de laboratoire ont été réalisés sur un modèle physique de pente de sol non-saturé, afin d'obtenir la valeur seuil du couple intensité-durée de précipitation qui déclenche un glissement de terrain. Seize essais de laboratoire ont été réalisés. Les principales conclusions de cette étude sont les suivantes: (1) Il est possible d'obtenir au laboratoire les seuils intensité-durée de la pluie (I-D) qui déclenchent un glissement de terrain, (2) la courbe du seuil I-D de déclenchement du glissement est partiellement linéaire dans un diagramme log-log, pour le sol utilisé dans cette étude, (3) en dessous d'une certaine intensité de la pluie (15 mm / heure dans cette étude) les glissements de terrain ne sont pas déclenchés pour les sols non saturés utilisés dans cette étude, (4) on observe qu'aucun glissement superficiel n'ait déclenché par les précipitations quand le sol est dense.

KEYWORDS: Rainfall triggered landslides, unsaturated soils, infiltration, slope stability

1 INTRODUCTION

Extreme and/or prolonged rainfall events frequently cause shallow landslides in many parts of the world including Turkey (e.g. Guzzetti et al. 2008, Nadim et al. 2009). Before rainfall, the ground is typically in an unsaturated/partially saturated state, where negative pore water pressure (suction) exists. As rainfall infiltrates into ground, water content of the unsaturated soil increases, suction decreases and shear strength of the slope decreases causing slope movements to develop. This process is controlled by many variables such as the intensity and duration of the rainfall, initial water content of the ground as well as the hydraulic and mechanical properties of the unsaturated soil. Therefore modelling of rainfall infiltration, seepage and slope stability requires comprehensive understanding of unsaturated soil mechanics.

Many researchers tried to obtain a threshold rainfall intensity-duration (I-D) curve (or a triggering cumulative rainfall amount) so that early warning can be established for a specific region. There exists some numerical studies which consider the physical mechanism of slope failure through infinite slope stability analysis, mostly applied spatially via Geographic Information Systems (Iverson et al. 1997, Crosta and Frattini 2003, Eichenberger et al. 2013). Other researchers used statistical evaluation of rainfall I-D thresholds based on archives of landslide and rainfall events (Caine 1980, Hong et al. 2006, Guzzetti et al. 2007 and Lu and Godt 2013). Laboratory physical modeling through flume experiments are used widely to model behavior of unsaturated slopes. Many researchers (e.g. Wang and Sassa 2001, Lourenco et al. 2006, Ochiai et al. 2007, Montrasio and Valentino 2007, Olivares et al. 2009, Fang et al. 2012, Zhou et al. 2013, Wu et al. 2015) have conducted laboratory flume experiments on sandy material subjected to rainfall and investigated their pre-failure and post-failure behavior and failure mechanisms.

In the current study the results of the laboratory flume experiments are used to develop I-D threshold and to investigate the effect of soil density on it.

2 EXPERIMENTAL STUDY

Soil used in current study is uniformly graded fine sand with 3% non-plastic fines. Grain size distribution (ASTM D6913), specific gravity of solids (ASTM D854), minimum/maximum void ratio and density in dry state (ASTM D4253 and D4254) and saturated hydraulic conductivity (ASTM D2434) of this soil are determined (Table 1).

Table 1. Properties of the soil used in this study

D_{10} (mm) :	0.09	Fines content (%) :	3
D_{30} (mm) :	0.14	USCS Soil Class.:	SP
D_{50} (mm) :	0.18	Gs :	2.663
D_{60} (mm) :	0.202	$\rho_{d\,max}$ (g/cm^3) :	1.648
C_c :	1.08	$\rho_{d\,min}$ (g/cm^3) :	1.332
C_u :	2.24	k_{sat} (m/s):	1.145×10^{-6}

Wetting Soil Water Characteristic Curve (SWCC) of the soil (at different dry densities) was assessed using capillary column method (Richards 1931) (Fig.1a). Properties of water transition through the soil samples were assessed using infiltration column method (ASTM D7664), to obtain the hydraulic conductivity function (HCF) of the soil (Fig.1b).

To study the infiltration and triggering of slope instability laboratory model experiments in flume setup are conducted with the application of artificial rainfall having a known intensity. Fig. 2 shows the schematic of the flume setup which consists of a flume box, raising system and adjustable rainfall system with mist sprinklers and instrumentation.

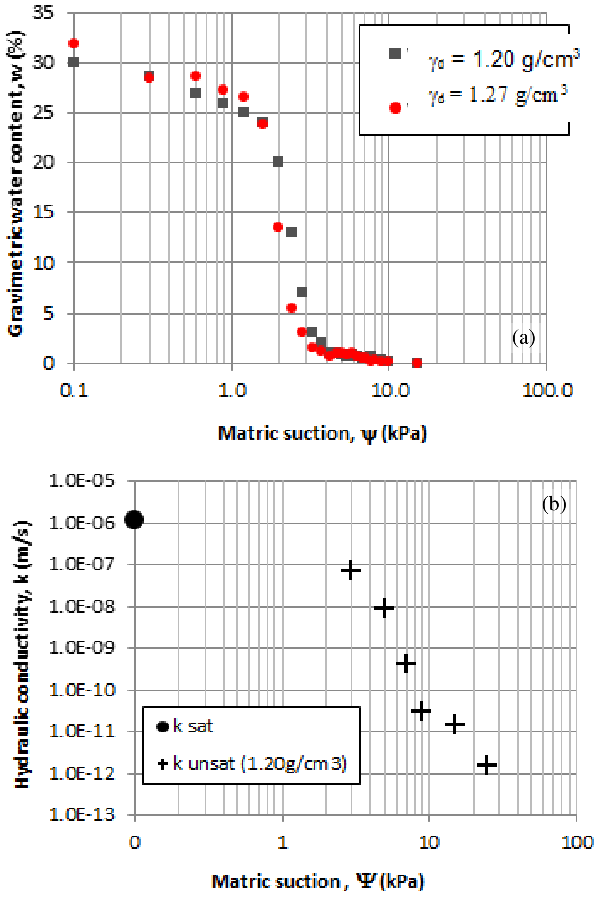


Figure 1. (a) Wetting SWCCs of the soil at different dry densities and (b) hydraulic conductivity of the soil obtained from infiltration column test.

The flume box can be tilted to desired inclinations up to 55 degrees from horizontal. The internal dimensions of the box are 187 cm (length) × 48 cm (width) × 70 cm (height). Two long faces of the box are made of tempered glass for allowing observations. Instrumentation used in this study are (i) miniature tensiometers (Soilmoisture 2100F) to measure 0-90 kPa suctions (abbreviated as TNS), (ii) miniature pore pressure transducer (Druck PDCR-81 by PROCON Systems Inc.) to measure positive and negative pore pressures (PDCR), (iii) in-house-developed miniature inclinometers (elastic woven/rubber strips) to detect slope deformations, and (iv) digital cameras (to obtain a video recording of deformations). Tensiometers and pressure transducers are inserted through an array of 12 mm diameter holes on one of the long (glass) faces of the box. Inclinometers were placed at the side and at the center of the slope. Side inclinometers were made of 5 mm wide black elastic bands/strips with white ink marks for measurement stations at 5 cm vertical spacing, and central inclinometers were made of very thin and very flexible (diameter of 1.0 mm) elastic strings with one tiny knot at measurement stations at 5 cm vertical spacing.

The rainfall system consists of a control box (composed of digital control panel, spraying-resting control circuit, water reservoir and actuators) and sprinkler array. Sprinkler array which supports pressurized water hoses and nozzles, is mounted on a frame with adjustable elevation and inclination. Nozzles spray water at constant flow rate. Therefore the system is capable of applying different rainfall intensities (that remain constant when averaged over each minute). The system was able to apply average rainfall intensities of 4-70 mm/h over the soil samples. Rainfall intensity was checked with small containers at each test, over each inclined surface tested, to make sure that rainfall is applied uniformly over the slope (Ahmadi-adli 2014).

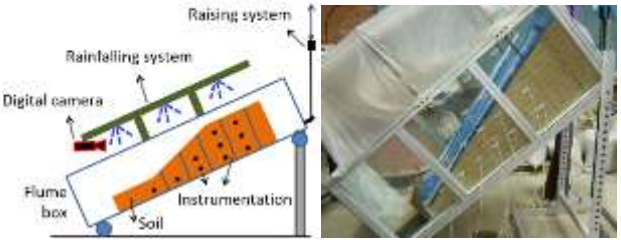


Figure 2. Schematic view of the flume setup

2.2. *Testing program*

In total 10 flume experiments are presented here, which are performed with different rainfall intensities. In each experiment, slope failure time was recorded (from the start of rainfall application time) in order to create threshold I-D plot. Variation of suction at each instrument location and wetting front progression over time and inclinometer measurements at the end of the experiment were also recorded.

In the flume experiments soil specimens were prepared at two relative densities of 34% and 48% corresponding to 1.20 and 1.27 g/cm^3 dry densities. Slope surface inclination in all flume experiments was 56.5 degrees from horizontal. Applied rainfall intensities are ranging from 18 mm/h (relatively low) to 63 mm/h (relatively high) intensities.

2.3. *Sample preparation*

The initial water content of sand is determined such that, when the sand gets wet, the volume of the sand, i.e. the initial dry density, does not change significantly and the sand can be easily placed and shaped. Sand is placed at an initial moisture content of 1.5%, in layers of 5 cm thickness and compacted to target density by tamping on a steel plate that is placed on the layer surface. The uniformity of soil placement is controlled by measuring its density using tares placed inside the soil while it is being prepared in trial tests. For all tests ±5% tolerance in soil density was controlled. The toe of the slope in the flume experiments is a drainage boundary, created by placing a granular filter material wrapped in filter paper. The bottom boundary of the flume box is impervious; however a geonet drainage material is placed to provide another drainage boundary along the inclined bottom boundary of the box.

3 RESULTS

3.1. *An example of flume experiment results*

Data obtained at each flume experiment are (i) suction-time response at specific points, (ii) wetting front progression with time and (iii) deformations and failure surface at the time of failure. Detailed results of all tests can be seen at Ahmadi-adli (2014). As an example, suction response recorded in the soil at different locations in FLM_04 test are plotted with time after the start of rainfall in Fig. 3 (b). The initial suction in the sample at different locations is measured to be in the range of 16.5 to 19.7 kPa before the rainfall is applied. While the 46.3 mm/h rainfall infiltrates into the soil, the suction values drop as the wetting front reaches to the level of each tensiometer. The earliest response is seen at TNS-01 (shallowest tensiometer, Fig. 3a) and the latest response at TNS-03 which is at the deepest location. Recordings in TNS-06 and TNS-08 start at suction values of 19-19.5 kPa and stay constant throughout the rainfall since failure occurred and the test ended before the water reached to the depth of these tensiometers, during the total rainfall duration of sixty eight minutes.

In order to assess the progress of wetting front with time in flume tests, the vertical distance between the wetting front (i.e. the depth where the water reaches and suction drops to zero) and the base of the flume setup were recorded from the glass side of the flume box at certain time intervals. Fig. 3 (c) shows the progress of wetting front with time for FLM_04 flume experiment. The failure is observed at 68 minutes after the start of rainfall at a depth of about 15 cm from ground surface at the deepest location. It is noticed that when failure occurred, the wetting front was at the depth of failure surface.

3.2. *Discussion of results*

In the tests with relative density of 34 % (FLM_03, 04, 05, 06, 08 & 13) except tests FLM_03 and FLM_13, the measured initial suction values at tensiometers is generally in the range of 17 to 21 kPa. At tests FLM_03 and FLM_13 higher initial suctions were recorded because of longer equalization time. Generally in all tests, tensiometers TNS_1, 2, 5 and 7 which were located at shallower depths, showed suction drop before the others do and then it was preceded with slope failure. But in tests with higher density (relative density of 48 %) almost all of active tensiometers showed suction drop before failure occurrence. In both category of tests at the lowest rainfall intensity (FLM_06 for R_d=34 % and FLM_15 for R_d=48 %) no failure was observed despite suction drop in all of the tensiometers. In tests with denser soil, the initial suction values were about 18.5-23.5 kPa.

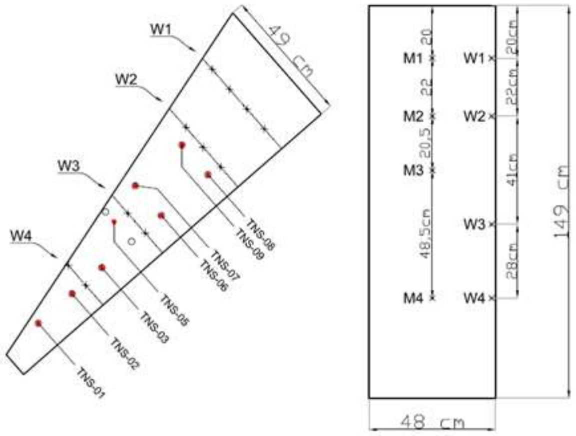
The failure surface and its depth is clearly observed from the side walls and excavation of side and central inclinometers after failure is observed. In Figure 3, W1-W4 indicate the location of side inclinometers (which are visible from the glass side of the flume box), and M1-M4 indicate the inclinometers located in the central section, at which failure surface can be observed after carefully exhuming after failure. Failures in all of the experiments follow the mechanism of shallow landslides triggered by rainfall i.e. failures are shallow and failure surfaces are nearly parallel to the surface of the slope. In all experiments that showed failure, the depth of failure surface (almost planar) ranges between 10 to 20 cm from ground surface (except in FLM_12 in which a partly-circular failure surface was observed). Possible local impurities during sample preparation could be the reason for part-circular failure surface.

3.3. *Rainfall Intensity-Duration threshold*

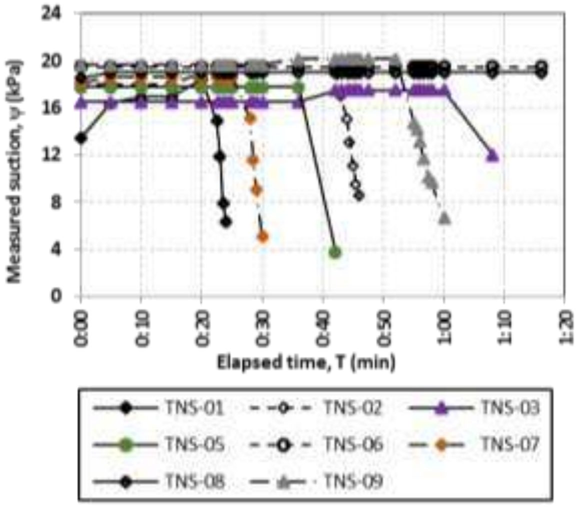
Plotting time to failure versus average rainfall intensity in flume experiments gives the rainfall I-D threshold that triggers a landslide. Fig. 4 shows the obtained I-D threshold for the two sets of tests with 34 and 48% relative density. Solid filled symbols in Fig. 4 represent the experiments which have experienced failure, whereas the experiments in which no failure is observed till the end of rainfall period are shown with data points with no filling. In almost all flume experiments, the deformations leading to failure occurred almost instantaneously, i.e. they are not slowly developing movements visible in the soil, but they occur rather abruptly.

For each of the relative densities of R_d=34% (FLM_03, 04, 05, 08 and 13) and R_d=48% (FLM_10, 12 and 14) a best function is fitted to the data on the I-D plot as a power function: I = a · D - b (I: rainfall intensity, D: rainfall duration, a and b are constants). The ‘a’ values for 34 and 48% relative densities are 38.1 and 134.9 and ‘b’ values are 1.556 and 1.431, respectively. These values are in the range of common values for ‘a’ (0.0 – 148.0) and ‘b’ (0.1 – 2.0) reported in the literature (Giannecchini 2005, Aleotti 2004, Guzzetti et al. 2008, Ma et al. 2015, IRPI database).

Overall, it is observed that the general shape of the I-D plot in log-log scale is linear. Current tests demonstrated physically that, low intensity-long duration rainfalls, and high intensity-short duration rainfalls can both trigger landslides (except the very small rainfall intensities, less than 15 mm/h for R_d=34% and 20 mm/h for R_d=48%). For very low intensity rainfalls, either the rainfall has to continue for a very long time to cause failure, or it is impossible to cause failure. The infiltration is at such a slow



(Side view) **(Top view)**



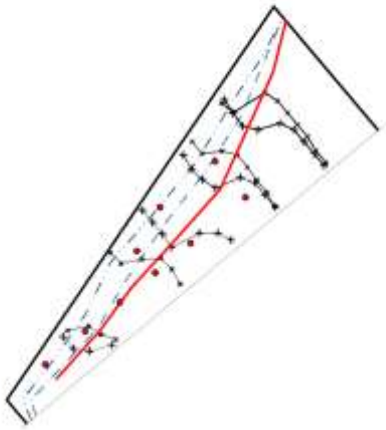


Figure 3. (a) Location of tensiometers and inclinometers in FLM_04 (side and top view), (b) suction response after start of rainfall (46 mm/h constant intensity) and (c) location of wetting front through the test, failure surface detected by inclinometers after failure (TNS: tensiometer).

rate that the water can percolate through the soil before it forms a wetting front and causes any slope instability.

The rainfall intensities applied in this study are in the range of 18-64 mm/h and duration ranges from less than 1 hour to about 13 hours. Although intensities are realistic, triggering rainfall durations were small as compared to real landslide-triggering rainfall events due to small scale of the model. The aim of the current study is, by no means, to propose an early warning threshold for a specific region. Instead, the goal is to trigger landslides by rainfall and obtain I-D thresholds experimentally and understand the physical mechanism.

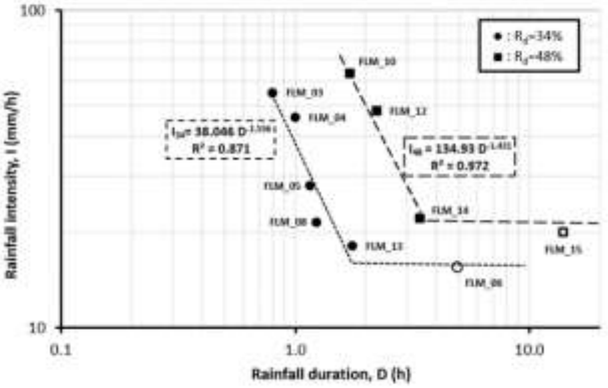


Figure 4. Rainfall intensity duration data obtained from flume tests

4 CONCLUSIONS

The major conclusions can be summarized as follows;

As the rainfall infiltrates into the soil, wetting front can be observed to move down and cause a reduction in suction in the ground (this is checked with tensiometers measuring a sudden drop of suction as the wetting front reaches to their locations). Wetting front in flume experiments generally were not in the shape of a perfect straight line along the slope length.

The landslide types are mostly translational, and failure mechanism can be categorised as infinite-slope type landslide. The failure surface is generally coincident with the wetting front or is in its vicinity. In flume experiments, the deformations leading to failure occurred abruptly (in less than 3 seconds).

The shape of the I-D threshold that triggers a landslide, is demonstrated to be a linear in log-log plot of rainfall intensity versus duration, for the soil used in this study. The results of this study confirms that, both high intensity-short duration rainfalls, and low intensity-long duration rainfalls can trigger landslides.

Below a certain rainfall intensity (in this study 15 and 20 mm/h for R_d=34% and R_d=48%) landslide is not triggered for the material used. This leads to a possible conclusion that the I-D relation could be asymptotic to a lowerbound rainfall intensity. For such low intensity rainfalls, either the rainfall has to continue for a very long time to cause failure, or it is impossible to cause failure in these very small rainfall intensities. A plausible reason for this is water entering at such a slow rate that it can be drained to the depths of soil by gravity before it causes any slope instability at the surface.

The effect of relative density of the soil on the I-D threshold is demonstrated by physical laboratory tests. As the relative density of the material increases, the triggering rainfall intensity-duration threshold line moves to larger rainfall events (in the log-log plot of intensity versus the duration), meaning having safer slopes for a specific rainfall in denser soil.

All of these conclusions are deduced for one type of soil (clean fine sand) used in this study; and that any further studies would strengthen the conclusions. The results of this study could be useful for future studies on physical and numerical modelling of rainfall-triggered landslides and early warning systems.

5 ACKNOWLEDGEMENTS

Funding was provided by Scientific & Technological Research Council of Turkey (TUBITAK) research project No. 109M635.

6 REFERENCES

Ahmadi-adli M. 2014. Shallow landslides triggered by rainfall in unsaturated soils. Ph.D. thesis, Middle East Technical University

Aleotti P. 2004. A warning system for rainfall-induced shallow failures. *Engineering Geology* 73: 247–265

ASTM. 2010. Standard test method for measurement of hydraulic conductivity of unsaturated soils. ASTM D7664. D-18

Caine N. 1980. The rainfall intensity - duration control of shallow landslides and debris flows. Phys Geog 62(1/2):23-27

Crosta G. and Frattini P. 2003. Distributed modelling of shallow landslides triggered by intense rainfall. *Nat. Hazards Earth Syst. Sci.* 3:81-93. doi:10.5194/nhess-3-81-2003

Eichenberger J., Ferrari A., Laloui L. 2013. Early warning thresholds for partially saturated slopes in volcanic ashes. Computers and Geotechnics 49:79-89. doi:10.1016/j.compgeo.2012.11.002

Fang, H., Cui, P., Pei, L. Z., & Zhou, X. J. 2012. Model testing on rainfall-induced landslide of loose soil in Wenchuan earthquake region. *Natural Hazards and Earth System Sciences*, *12*(3), 527-533.

Giannecchini R. 2005. Rainfall triggering soil slips in the southern Apuane Alps (Tuscany, Italy). *Advances in Geosciences* 2: 21-24

Guzzetti F., Peruccacci S., Rossi M., Stark C.P. 2007. Rainfall thresholds for the initiation of landslides in central and southern Europe. *Meteorology And Atmospheric Physics* 98(3-4):239-267

Guzzetti F., Peruccacci S., Rossi M., Stark C.P. 2008. The rainfall intensity-duration control of shallow landslides and debris flows: an update. *Landslides* 5: 3-17

Hong Y., Adler R., Huffman G. 2006. Evaluation of the potential of NASA multi-satellite precipitation analysis in global landslide hazard assessment. *Geophysical Research Letters* 33(22)

IRPI, Rainfall thresholds for the initiation of landslides, http://wwwdb.gndci.cnr.it/php2/rainfall_thresholds/thresholds_all.php?lingua=it, accessed on 19 May 2016.

Iverson R.M., Reid M.E., LaHusen R.G. 1997. Debris-flow mobilization from landslides 1. *Annual Review of Earth and Planetary Sciences* 25(1):85-138

Lourenco S., Sassa K., Fukuoka H. 2006. Failure process and hydrologic response of a two layer physical model: Implications for rainfall-induced landslides. *Geomorphology* 73: 115-130.

Lu N. and Godt J.W. 2013. Hillslope hydrology and stability. Cambridge University Press, Cambridge.

Ma T., Li C., Lu Z., Bao Q. 2015. Rainfall intensity–duration thresholds for the initiation of landslides in Zhejiang Province, China. Geomorphology 245:193-206

Montrasio L. and Valentino R. 2007. Experimental analysis and modelling of shallow landslides. *Landslides* 4(3): 291-296. doi:10.1007/s10346-007-0082-3

Nadim F., Cepeda F., Sandersen F., Jaedicke C., Heyerdahl H. 2009. Prediction of rainfall-induced landslides through empirical and numerical models. In: Proceeedings of IWL - The First Italian Workshop on Landslides. Naples, 8/10 June 2009 (1):206-215

Ochiai, H., Sammori, T., & Okada, Y. 2007. Landslide experiments on artificial and natural slopes. *Progress in landslide science*, 209-226.

Olivares L., Damiano E., Greco R., Zeni L., Picarelli L., Minardo A, Guida, A., Bernini R. 2009. An Instrumented Flume to Investigate the Mechanics of Rainfall-Induced Landslides in Unsaturated Granular Soils. *Geotechnical Testing Journal* 32(2):1-11

Richards, L.A. 1931. Capillary conduction of liquids through porous mediums. Physics 1 (5): 318–333.

Wang G. and Sassa K. 2001. Factors affecting rainfall-induced flowslides in laboratory fume tests. *Geotechnique* 51(7):587-599

Wu, L. Z., Huang, R. Q., Xu, Q., Zhang, L. M., & Li, H. L. 2015. Analysis of physical testing of rainfall-induced soil slope failures. *Environmental Earth Sciences*, *73*(12), 8519-8531.

Zhou, J., Li, Y. X., Jia, M. C., & Li, C. N. 2013. Numerical simulation of failure behavior of granular debris flows based on flume model tests. The Scientific World Journal, 2013.