Assessment of Variation in Degree of Saturation Due to Rainfall for Landslide Study

Prashant Sudani[1] and K. A. Patil[1]
[1]*Department of Civil Engineering, College of Engineering Pune, Pune, India*
E-mail: *sudaniprashant93@gmail.com*

ABSTRACT: A landslide is a mass movement of the earth under gravity due to natural or man-made triggering events. Foremost of the landslides in humid countries like India are rainfall-induced landslide movements. Rainfall tends to infiltrate into the slope, leading to the recharge of the soil mass with water, which depends on the void present in the medium. This water content in the slope mass alters the slope-forming soil's properties in many ways, i.e., increasing the weight of the slope soil, reducing the soil strength, increasing pore water pressure, and changes in the geotechnical properties of the soil mass. Numerous models are available for predicting landslides based on water present in the soil. However, the link between rainfall precipitation and corresponding real-time monitoring of water stored in the soil system is still missing. Variation in the saturation is required to be assessed corresponding to rainfall events. The present study aims to monitor the variation in the degree of saturation in the soil mass corresponding to rainfall. The leaky barrel concept is used to model the test setup for deriving the saturation evolution in the soil mass. The output of the research interpretation successfully mapped the variation in the water saturation for the soil mass associated with rainfall events.

KEYWORDS: Landslide, Degree of saturation, and Leaky barrel.

1. INTRODUCTION

Landslide is disastrous and consistently associated with considerable losses to society, infrastructure, and innocent animals. The term "Landside" can define as "Mass movements of the soil mass under gravity towards the bottom of the slope due to loss in strength supporting the slope." Rainstorm-induced landslide hazards are often found in humid countries like India, where 1/3rd of the year has precipitation and the remaining 2/3rd of the year has a humid and hot climate (Ering & Babu, 2016; Kunnath & Ramesh, 2010; Ramesh, 2014; Sudani & Patil, 2022a, 2022b). Saturation in the soil starts to build once rainfall initiates the infiltration into the slope mass. With the increasing amount of water in the soil mass of the slope, properties of the soil tend to alter, i.e., saturation leads to increasing the unit weight of the earth, which supports the deriving force of the landslide and affects the factor of safety negatively; it also leads to decreasing the shear strength of the soil to the significant level which otherwise impacts the resisting force to the landslide, saturation of the soil reduces the capillary suction (matric suction) of the soil which hold the soil together by suctioning effect on them, and also a higher degree of saturation leads to increase in the pore water pressure into the soil-forming slope which leads to making a negative impact on the stability of the hill.

Severe rainstorms often trigger the shallow slopes, which mobilize into the mudflow in several parts of India, susceptible to landslide hazards, i.e., the Himalayan region, Western Ghat, and the northeast part of the country (Patil V. & Gopale R., 2018; Sarvade et al., 2017; C. R. Shah et al., 2021; Singh et al., 2016). These mudslides suddenly initiate and move at a rapid rate of 15 m/sec or more, covering distances as many kilometers. Mudflow can destroy houses, damaged roads and bridges, wipe out trees and vehicles, and when it finally comes to rest, deposit several thousand cubic meters of mud in surrounding areas, which can bury infrastructure, block roads, and make a high chance of casualties.

Water is the prominent harm that makes losses in the shear strength, makes the soil more plastic, and initiates the debris flow. Water saturation initiation in the slope reduces the capillary forces (matric suction) in the hill, which otherwise holds the soil together and supports stability. Nieto & Barany (Nieto & Barany, 1988) proposed that a simple reduction in the matric suction (negative pore water pressure) can trigger the landslide without attaining positive pore water pressure. There is also diversification in the opinions of the various researchers about how the actual rainfall triggers slope failure. A group of researchers states that the buildup of the zone of saturation increases the positive pore water pressure, reduces the effective stress, and decreases the strength governing parameters called cohesion and angle of internal friction, making the material weak; hence it fails the slope (Fredlund & Anqing Xing, 1994; Macciotta et al., 2016; Russo, C., Chan, D., & Picarelli, 2004; M. V. Shah & Sudani, 2020; Terzaghi, 1950; Walde et al., 2017). Another group of researchers finds seepage forces responsible for slope failure, which causes the drag on the soil particles and makes them fail (Ikard et al., 2015; Johansson, 1997; Panthulu et al., 2001; Taylor, 1948). Water in the slope or saturation in the soil is not a permanent water table. Still, it is a temporary storage of the water above permeability discontinuity during the rainstorm event, which is otherwise in an unsaturated state. After cessation of the rainfall, this saturation decreases, making them difficult to estimate or monitor.

This study analyzes the saturation evolution in the soil due to intense rainstorm events. The overall aim is to monitor the saturation variation in the soil containing slopes corresponding to the rainfall. Rainfall always initiates the infiltration from the open surface of the hill, which starts to diffuse in the soil in all directions. Part of it fills the voids present in the soil, and another part of it percolates into the groundwater channel. The rate, i.e., the rate at which water infiltrates into the ground surface and percolates through it, is different (Fiorillo & Wilson, 2004; Wilson & Wieczorek, 1995). The study uses these variations in the rate of infiltration and percolation to map the saturation evolution in the soil.

2. METHODOLOGY

Storage of the infiltrated drain water into the soil mass of the slope could be replicated by a numerical model based on the leaky barrel concept (Wilson & Wieczorek, 1995). This leaky barrel model is similar to the "tank model" used for rainfall-runoff simulation in Japan and is also used in landslide prediction (e.g., Hiura & Sassa, 1985). The leaky barrel model simulates the evolution of rainfall into water saturation. The leaky barrel model consists of a cylinder, open at the top to receive the rain, and a water collection system at the bottom for percolation measurement through the soil sample.

The test setup for the leaky barrel model was fabricated from the Poly Vinyl Chloride (PVC) material. The model was cast in a cylindrical shape with a 110 mm diameter and 250 mm height. For estimating the infiltration rate, the top 50 mm of the model's size were cast in the thread marks so it could store the 20 ml of water for one thread. At the bottom of the model, a perforated disk was set up to allow the water to percolate and move out from the soil system. The entire leaky barrel test setup is shown here in Figure 1.

Figure 1 Leaky barrel model test setup

Soil samples were used to fill in the cylindrical barrel at field density and moisture content. To achieve the field density in the mold required weight of the dry soil according to the field dry density of the soil and volume of the cylinder were used to fill in the model, and the density of the sample was adjusted by the cycle of wetting and drying until it's become similar to that in-situ density. Further water is introduced on the top of the model drop by drop until water moves out from the bottom outlet. Every test is performed for one week to allow even diffusion of the retained water in the void of the soil sample. At the time when water first started to accumulate in the bottom, capillary porosity would thoroughly saturate, and matric suction would become zero. The further accumulation of the water in the system would generate positive pore water pressure in the soil. Further, the water is allowed to infiltrate into the soil mass, and the corresponding percolation of the water is recorded. The difference between the infiltration and percolation yields the storage, further providing a degree of saturation through basic soil properties, i.e., void ratio and specific gravity.

3. RESULTS AND DISCUSSIONS

The present study is part of PhD research on the development of landslide early warning system. Soil used in the study are procured from Malin Hill slope located in Western Ghat of India. Malin hill suffered a disastrous landslide in 2014, which caused burial of an entire village under debris. The present research aims to monitor the saturation variation in the soil slope with back analysis of the Malin hill slope. Basic geotechnical properties of soil are presented in Table-1.

Table 1 Basic Geotechnical properties of soil

Sr. No.	Description	Unit	Malin soil	Reference
1	Natural water content	%	8.60	ASTM D 4643
2	Specific gravity	NA	2.70	ASTM D 854
3	Liquid limit	%	41	ASTM D 4318
4	Plastic limit	%	29.66	ASTM D 4318
5	Plasticity index	%	11.34	ASTM D 4318
6	Classification	NA	MI	ASTM D 2487
7	Hydrometer	%	5.85/66.15/28 Clay/Silt/Sand	ASTM D 7928
8	OMC	%	21.0	ASTM D 698
9	MDD	gm/cc	1.64	ASTM D 698
10	Cohesion	kg/cm2	0.708	ASTM D 3080
11	Angle of internal friction	°	33.88	ASTM D 3080
12	Permeability	cm/sec	5.74 ×10-6	ASTM D 5856

The leaky barrel concept is used to model the test setup for deriving the saturation evolution in the soil mass. The overall aim is to monitor the saturation variation in the soil containing slopes corresponding to the rainfall. Rainfall always initiates infiltration from the slope's open surface, which starts to diffuse in the soil in all directions. Part of it fills the voids in the soil, and another part will percolate into the groundwater channel. Both the rate, i.e., the rate at which water infiltrates into the ground surface and the rate at which it percolates through it, are different (Wilson & Weickzork, 1995). The study uses these variations in the rate of infiltration and percolation to map the saturation evolution in the soil. The output of the research interpretation successfully maps the variation in the water saturation for the soil mass associated with rainfall events.

During the dry state of slope soil, the suction (negative pore water pressure) in the soil will be at its peak. Once the soil was fully saturated (Sr = 100%), positive pore pressure would dominate at its peak value. The soil would attain zero water pressure between these negative pores and maximum positive pressure at some point. Their field capacity represents volumetric water content at which soil reaches zero pore water pressure. The field capacity of the Malin village slope soil is determined by preparing the soil sample in the cylindrical barrel at field density and moisture content. To achieve the field density in the mold required weight of the dry soil according to the field dry density of the soil and volume of the cylinder were used to fill in the model, and the density of the sample was adjusted by a cycle of wetting and drying until it's become similar to that in-situ density.

Further water is introduced on the top of the model drop by drop until water begins to move out from the bottom outlet. Every test is performed for one week to allow even diffusion of the retained water in the void of the soil sample. When the water started accumulating in the bottom, capillary porosity would completely saturate, and matric suction would become zero. Further accumulation of the water in the system would generate positive pore water pressure in the soil. Further, the water is allowed to infiltrate into the soil mass, and the corresponding percolation of the water is recorded.

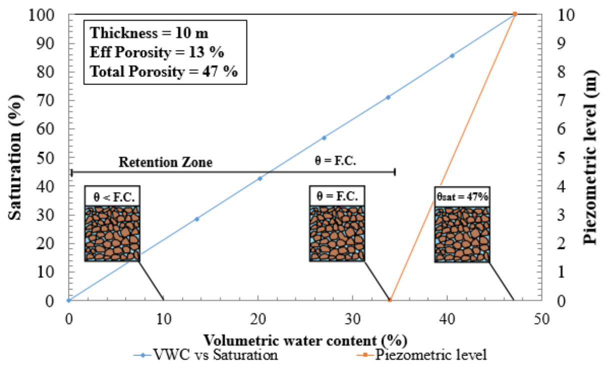

Figure 2 VMC, Saturation, and Piezo metric relationship for Malin soil

Figure 2 shows the water accumulation in the top 10 m of the weathered soil of the Malin village hill slope beyond this depth, basalt rock is present, which constitutes impermeable barrier to the water (Prashant 2023). Initially, the soil was in a dry state (Sr = 0%), with porosity n = 0.47. For volumetric water content (VWC) θ, up to 34%, water is accumulated and retained in capillary porous. Effective porosity is the difference between total porosity and the field capacity at which soil attains zero matric suction. In this case, effective porosity (n_{eff}) is 0.47 – 0.34 = 0.13. This shows that after attaining zero pore water pressure within 13% of the positive variation in volumetric water, the content would lead the piezometric line to 10 m (Figure 2). The volumetric water content θ will vary between maximum value θmax = Field capacity, representing zero suction, and minimum value θmin, representing soil status in the summer season. The amount of excess water, θ > θ max, may have been stored temporarily and removed from the system by percolation.

Storage of the infiltrated rainwater into the soil mass of the slope could be replicated by a numerical model based on the leaky barrel concept (Wilson 1989). This leaky barrel model is similar to the "tank model" used for rainfall-runoff simulation in Japan and is also used in landslide prediction (e.g., Hiura and Sassa, 1985; Kobashi and Suzuki, 1987). The leaky barrel model simulates the evolution of rainfall into water saturation. The leaky barrel model consists of a cylinder, open at the top to receive the rainfall, and a water collection system at the bottom for percolation through the soil sample (Figure 3).

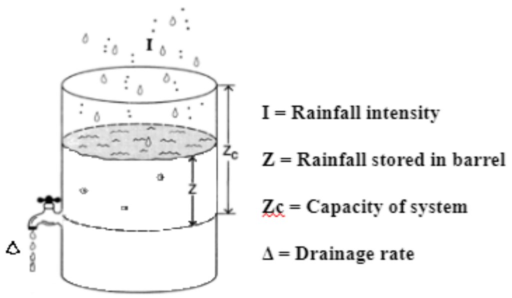

Figure 3 Graphical setup of Leaky barrel

Here denoted by "Z," water temporarily retained in the system represents free pore water in the zone of saturation. The leaky barrel system's drainage rate is assumed to be linearly proportional to the water stored in system "Z." The proportionality constant, K_d, represents the drainage coefficient, and its unit is the inverse of time.

$$Drainage\ Rate = K_d \cdot Z \tag{1}$$

Where, Z = Water stored in a system K_d = Drainage co-efficient

The amount of water retained in soil will increase or decrease depending on the rainfall intensity (I(t)) and drainage rate ($K_d \cdot Z$). Net variation in water stored in the system can be stated as a linear first-order differential equation,

$$\frac{dZ}{dt} = I(t) - K_d \cdot Z \tag{2}$$

Where, I = Intensity of rainfall t = time

Now for monitoring the water stored in the soil system, we have to consider two cases, i.e., 1) an increase in the stored water during rainfall and 2) decreasing retained water in the soil after rainfall has ceased, as suggested by Wilson, 1989. During rainfall, the level of retained water in the soil system Z(t) is given by the relation:

$$Z(t) = \frac{I}{K_d}\left(1 - e^{-K_d \cdot t}\right) \tag{3}$$

After the rainfall ceases, amount of water retained in soil "Z" drain back to zero by logarithmically decreasing function:

$$Z(t*) = Z_0\left(e^{-K_d \cdot t*}\right) \tag{4}$$

Where, Zo = Retained water in the soil sample when rainfall ceases, t* = Time elapsed since rainfall has ceased generalized good numerical simulation can be derived by superimposing both the case by developing one algorithm, which will provide the continuous monitoring of water stored in soil corresponding to the rainfall events in real-time:

$$Z_n = (Z_{n-1})\left(e^{-K_d \cdot \Delta t}\right) + \frac{I(t)}{K_d}\left(1 - e^{-K_d \cdot \Delta t}\right) \tag{5}$$

This combined approximation of numerical simulation would monitor the water stored in the system step by step. Where the subscript "n" represents the "Step" of the time sequence, Δt is time increment, and I(t) is rainfall intensity during the considered time step. The water stored in the soil system Zn can be calculated by iteration for each time step in the rainfall records. This algorithm may be easily programmable on a computer.

The test setup for the leaky barrel model was fabricated from polyvinyl chloride (PVC) material. The model was cast in a cylindrical shape with a 110 mm diameter and 250 mm height. To estimate the infiltration rate, the model's top 50 mm height was cast in the thread marks so it could store the 20 ml of water for 1 thread. At the bottom, the perforated disk was set to allow the water to percolate and drain from the soil system. The entire leaky barrel test setup is shown here in Figure 1.

Soil was remolded in the cylindrical barrel at field density & moisture content. To achieve the field density in the mold required weight of dry soil according to the field dry density was used to fill in the model, and the density of the sample was adjusted by wetting and drying cycle until it's become similar to that in-situ density. Further water is introduced on the top of the model drop by drop until water begins to move out from the bottom outlet. Every test is performed for one week to allow diffusion of the retained water in the void of the soil sample. Further, the water is allowed to infiltrate into the soil mass, and the corresponding percolation of the water was recorded.

Through continuous monitoring of the drainage rate and water stored in the soil system, the drainage coefficient of the Malin hill slope soil is equal to 0.041/hr. Further, for the present research, rainfall data for 2014 (The landslide year) was collected from the rain gauge adjacent to the Malin village landslide location (Figure 4).

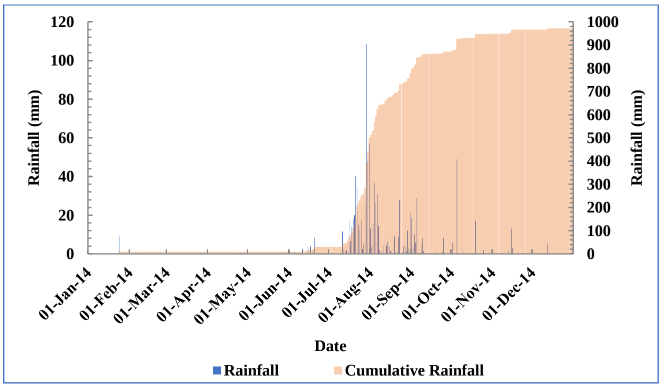

Figure 4 Rainfall data of Malin village landslide location of the 2014 year (Landslide year)

From the rainfall records of Malin, it is observed that heavy rainfall was present exactly before landslide day (29th July 2014). Even on the day of the landslide, rainfall at the location of 108.5 mm was reported. This rainfall was responsible for the Malin landslide. This day-to-day rainfall record is used to run the iteration process of the numerical approximation of the algorithm. Each iteration provides the degree of saturation at the end of that day. A complete iteration process of the Malin village location was carried out, and the results are presented here in Figure 5.

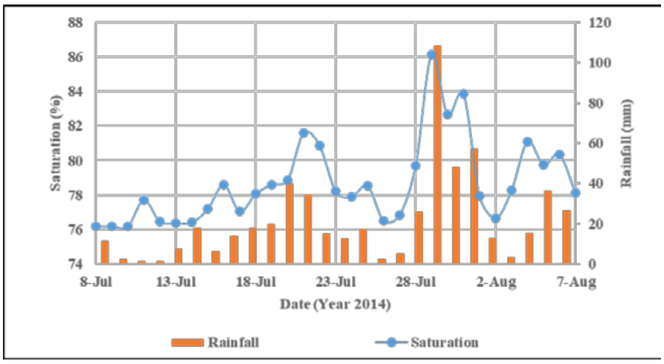

Figure 5 Monitoring of water saturation in the slope soil corresponding to the daily rainfall

Figure 5 represents the output of the leaky barrel algorithm, which provides the iterative approximation steps for predicting the water stored in the soil system. It was found that on the day of the landslide, the percentage of water saturation in the land slope was 86.5%. Stability analysis of the land slope predicted the failure if water saturation increased over 87%. The research output, along with rigorous stability analysis through limit equilibrium analysis and saturation evolution monitoring, can predict the landslide at the study location, which was validated by landslide incidence in Malin village on 29th July 2014.

4. CONCLUSIONS

The study represents the assessment of variation in the water saturation at the soil slope corresponding to rainstorm events. The evolution of the water accumulation in the soil slope is crucial to monitoring the land slope stability as it affects the several strength governing parameters of slope soil. The study found a unique way of tracking the saturation in the soil mass by water balance through a leaky barrel experimental setup. It reveals the following conclusions:

- The leaky barrel model test setup successfully maps the infiltration capacity and soil drainage rate at field density.
- The study effectively monitors the water saturation variation in the soil mass due to precipitation.
- Negative and positive pore pressure can be monitored by having the soil water characteristics curve on hand.
- Landslide monitoring could be done based on the saturation variation in the slope and their corresponding stability simulation.
- Real-time water saturation monitoring was done through a leaky barrel experimental-based algorithm, which successfully maps the accurate water saturation in the slope corresponding to the rainfall. Results show that on 29th July 2014, saturation reached 86.5%, which is very close to the landslide predicting saturation level. On the same day, the landslide was reported at the study location, validating the entire research.

Effective monitoring of the water saturation in the soil mass containing slope is crucial in developing the landslide early warning system; the study has the potential to map it.

5. REFERENCES

Ering, P. and Babu, G. L. S. (2016). “Probabilistic Back Analysis of Rainfall Induced Landslide - A Case Study of Malin Landslide, India.” *Engineering Geology*, 208, 154–164. https://doi.org/10.1016/j.enggeo.2016.05.002.

Fiorillo, F. and Wilson, R. C. (2004). “Rainfall Induced Debris Flows in Pyroclastic Deposits, Campania (Southern Italy).” *Engineering Geology*, 75(3–4), 263–289. https://doi.org/10.1016/j.enggeo.2004.06.014.

Fredlund, D. G. and Anqing Xing. (1994). “Equations for the Soil-Water Characteristic Curve.” *Canadian Geotechnical Journal*, 31(4), 521–532. https://doi.org/10.1139/t94-061.

Hiura, H. and Sassa, K. (1985). “Estimation of the Landslide Drainage Effect in Use of Tank Model.” *In A. Takei (Ed.), Proceedings of International Symposium on Erosion, Debris Flow and Disaster Prevention*, 355–360.

Ikard, S. J., Rittgers, J., Revil, A., and Mooney, M. A. (2015). “Geophysical Investigation of Seepage Beneath an Earthen Dam.” *Groundwater*, 53(2), 238–250. https://doi.org/10.1111/gwat.12185.

Johansson, S. (1997). “Seepage Monitoring in Embankment Dams.” *In Doctoral Dissertation, Department of Civil and (Issue February)*, http://kth.diva-portal.org/smash/get/diva2:8066/FULLTEXT01.

Kunnath, A. T. and Ramesh, M. V. (2010). “Integrating Geophone Network to Real-Time Wireless Sensor Network System for Landslide Detection.” 167–171. https://doi.org/10.1109/sensordevices.2010.38.

Macciotta, R., Hendry, M., and Martin, C. D. (2016). “Developing an Early Warning System for a Very Slow Landslide Based on Displacement Monitoring.” *Natural Hazards*, 81(2), 887–907. https://doi.org/10.1007/s11069-015-2110-2.

Nieto, A. S. and Barany, I. (1988). “Interim Report on Catastrophic Rain-Induced Landslides in Rio de Janeiro and Petropolis, Brazil.” *Report to Committee on Natural Disasters, National Resource Council.*

Panthulu, T. V., Krishnaiah, C., and Shirke, J. M. (2001). “Detection of Seepage Paths in Earth Dams Using Self-Potential and Electrical Resistivity Methods.” *Engineering Geology*, 59(3–4), 281–295. https://doi.org/10.1016/S0013-7952(00)00082-X.

Patil V. and Gopale R. (2018). “A Geographical Study of Landslide: A Case Study of Malin Village of Ambegaon Tahsil in Pune

District, Maharashtra." *Peer Reviewed International Research Journal of Geography,* 35, 55–60.

Ramesh, M. V. (2014). "Ad Hoc Networks Design, Development, and Deployment of a Wireless Sensor Network for Detection of Landslides." *Ad Hoc Networks,* 13, 2–18. https://doi.org/10.1016/j.adhoc.2012.09.002.

Russo, C., Chan, D., and Picarelli, L. (2004). "Role of Viscous Soil Properties on Landslide Movement Triggered by Pore Water Fluctuations." *Landslides: Evaluation and Stabilization,* 1189–1194.

Sarvade, S. M., Sarvade, M. M., Khadatare, P. S., and Kolekar, M. R. (2017). "30/7 Malin Landslide: A Case Study. September."

Shah, C. R., Sathe, S. S., Bhagawati, P. B., and Mohite, S. S. (2021). "A Hill Slope Failure Analysis: A Case Study of Malingoan Village, Maharashtra, India." *Geology, Ecology, and Landscapes,* 5(1), 1–6. https://doi.org/10.1080/24749508.2019.1695714.

Shah, M. V. and Sudani, P. (2020). "Strength and Deformation Characteristics of Laterite Rock with Different Rock Matrix's Using Triaxial System." 85–102. https://doi.org/10.1007/978-3-030-34178-7_8.

Singh, T. N., Singh, R., Singh, B., Sharma, L. K., Singh, R., and Ansari, M. K. (2016). "Investigations and Stability Analyses of Malin Village Landslide of Pune District, Maharashtra, India." *Natural Hazards,* 81(3), 2019–2030. https://doi.org/10.1007/s11069-016-2241-0.

Sudani, P. and Patil, K. (2022a). "Geo-Mechanical Behavior of Toe Excavated Land Slope." *International Journal of Mechanical Engineering*, 7.

Sudani, P. and Patil, K. A. (2022b). "Evolution of Early Warning System for Landslides." *Disaster Advances,* 15(8), 46–59. https://doi.org/10.25303/1508da046059.

Sudani, P. and Patil, K. A. (2023). "Effect of Water Saturation on Stability of Hill Slope: Malin Case Study." *Advances in Civil and Architectural Engineering.*

Taylor, D. W. (1948). "Fundamentals of Soil Mechanics." LWW, Vol. 66.

Terzaghi, K. (1950). "Geologic Aspects of Soft-Ground Tunneling."

Walde, S., Kale, K., Kundu, S., Nagaraj, P., Shelar, T., & Kumar Shukla, V. (2017). "GIS Based Landslide Susceptibility Assessment of Malin Area: A Case Study in Watershed, India."

Wilson, R. C. and Wieczorek, G. F. (1995). "Rainfall Thresholds for the Initiation of Debris Flows at La Honda, California." *In Environmental & Engineering Geoscience*, Vol. 1, issue 1, 11–27. https://doi.org/10.2113/gseegeosci.i.1.11.