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Study of Rainfall Thresholds for Landslide in Soil Slopes Based on Numerical Modeling

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Abstract
Rainfall thresholds can be useful in predicting vulnerability of slopes to landslides. Many available thresholds around different parts of the world including Nepal have been determined empirically by correlating actual landslides to the rainfall events that triggered it. Considerable amount of research is also available regarding rainfall characteristics of Nepal. Parameters important in cases of rainfall induced instabilities have also been investigated by various authors via numerical modeling. But investigation of some parameters is still lagging. Numerical models were prepared taking into consideration various aspects of natural soil slopes susceptible to landslides, and rainfall characteristics of Nepal. Effect of parameters namely depth of soil, permeability of bed rock, angle of slope and length of slope were investigated and it was found that each formerly mentioned parameter affected the threshold rainfall more in comparison to the later. An Intensity-Duration relationship of $I = 34.028D^{-0.591}$ was also obtained.

Keywords
Rainfall Threshold – Landslides – Intensity-Duration Relationship

1. Introduction

Rainfall threshold is the amount of precipitation in the form of rain, that when continued for certain duration would trigger landslides. Understanding of relation between rainfall thresholds and parameters related to it can be valuable in assessing landslide problems, especially in Himalayan region, where Landslide hazards are very frequent. Landslide related problems are prominent in Himalayan region, which alone contributes to 30% of the world's total landslide related damage [1]. Also, rainfall is one of the most important triggering factors for landslides in soil slopes. Importance of rainfall thresholds can be realized from the case, where out of 27 landslides and debris flows predicted by Li and Wang in light of landslide triggering precipitation, 25 actually occurred in their study area in Himalayas [2, 3].

Several rainfall thresholds have been proposed for different parts of the world on empirical basis. The empirical rainfall threshold concept can be applied very simply to the assessment of rainfall-induced landslide, but it provides very little insight into the actual physical processes that trigger landslide[4]. In regards to numerical modeling, advancements have been made in understanding of how change in various parameters such as duration of antecedent and major rainfall[5], rainfall pattern[6], permeability of soil[5], and initial conditions of pore-water pressure[5] affect the stability of slopes. Yet, some parameters have been left out in investigations. Also, researches based on numerical modeling so far have been more inclined towards the output of factor of safety and not the Rainfall threshold itself. Some Rainfall thresholds for shallow landsliding have been achieved by deterministic numerical modeling. An example of this would be Seattle, Washington, area, [7], but the study is done without considering the effect of factors such as the permeability of bed rock and variation in soil thickness.

Considering these gaps in research, the variation of rainfall thresholds for landslides in soil mass along with changes in parameters namely, depth of soil, permeability of bed rock, angle of slope and length of slope were studied in this research by sensitivity analysis, and an intensity-duration relationship of threshold rainfall is also proposed in this paper. The GeoStudio 2007 package along with some functions of the GeoStudio 2004 have been used in this research for conducting numerical modelings. The transient seepage analyses were conducted on the SEEP/W models of Geo-studio 2007. The pore water pressures obtained from seepage analyses were included in the SLOPE/W models of GeoStudio 2007 to conduct slope stability analyses. Data input required for analyses were selected in consideration of various relevant literatures, major proportions of which are related to Nepal.

2. Modeling Approach

The generally conducted process of slope stability analysis for convenience is, analyzing the slope under full saturation. But, this does not depict actual mechanism of landslides. The possibility of full saturation under heavy rainfall in itself is a question. Such problems have to be assessed by use of unsaturated soil mechanics, because lower the saturation level of soil is, lower becomes its ability to store and conduct water, and the soil above ground water table has negative pore pressure with respect to atmospheric pressure. Thus, the permeability of soil is not a constant, but a variable which decreases with rise in negative pore pressure. If the negative pore-pressure is high enough, the permeability of soil may get so low that even higher intensities of rainfall cannot bring the soil to saturation. The matric suction also imparts additional strength in soil. Such higher negative pore pressure values may occur where soil depth is high and ground water table is low prior to rainfall event.

This is where importance of antecedent rainfall in triggering landslides can be felt. Antecedent rainfall prior to landslide triggering rainfall, is a very important factor in rendering a slope unstable. Antecedent rainfalls of relatively longer durations, despite of their lower intensities, gradually increase the permeability of soil and decrease its strength, so that significant infiltration from major rainfall is possible.

2.1 Soil Depth

Weathering on slopes of the uplifted parent rocks is what creates the soil on the mountain slopes [8]. But since the rate of erosion is more than rate of soil formation in steep slopes, the slopes steep enough to produce landslides generally have shallow soil cover. The first author of this paper has also observed from various literatures[9, 10, 11, 12]that the depth of soil in several landslides in Nepal, involving soil mass movement, were generally shallow. Therefore, relatively shallow soil depths were modeled during this research.

2.2 Rainfall Input

Satisfactory estimation of pore pressure distribution and ground water table condition can be done by simulating a start-up time prior to our time of interest. A startup time of 10 days is usually sufficient to get the initial pore pressure distribution[13]. This means, even in conditions of different initial pore-pressures, if the same form of 10 day precipitation is applied to slopes having different initial conditions, the final pore pressure distribution will be similar. In a different research, 10 days of antecedent rainfall has also been observed to be related with the threshold rainfall with much higher correlation than other durations of antecedent rainfall in Nepal[14]. Therefore, an input duration of 10 days of antecedent rainfall was taken in every rainfall simulation in this research prior to heavy rainfall. The ground water table required in GeoStudio is modeled just above bed rock.

In general, the total pre-monsoon and monsoon rainfall in Nepal are 12% and 80% of the total annual rainfall respectively. While the pre-monsoon lasts for about 3.5 months, the monsoon is generally of 3 months in duration[3]. When equally distributed over their respective durations, the ratio between average daily monsoon rainfall and average daily pre-monsoon rainfall is 70:9 i.e. about 7.77 in Nepal. The same ratio was selected for simulation between the daily threshold rainfall and daily antecedent rainfall. Whenever variations were done in rainfall values, this ratio was maintained in each simulation. It was thus assumed that the initial conditions prior to landslide triggering rainfall are developed at least to the conditions of pore-water pressure and ground water table generated by pre-monsoon rainfall.

Rainfalls were applied in Geo-studio models as hydraulic boundary condition with potential seepage face review. Hence, rainfall in excess of infiltration is taken as runoff and no ponding of water takes place at the surface. Every rainfall function as Hydraulic boundary condition is comprised of 10 days of antecedent rainfall followed by threshold rainfall in varying duration. The duration of threshold rainfall for sensitivity analysis was taken as 1 day. For observing the Intensity-Duration relationship, duration of threshold rainfall were varied as 10 hours, 1,2,3,4,7 and 10 days.

2.3 Permeability of bed rock

Permeability offered by bed rock, another parameter that is often ignored in analysis plays an important role in pore pressure development in a transient process by allowing drainage from soil mass. The rock mass itself has not been modeled in this study, but the permeability offered by bed rock has been modeled as boundary condition below the soil region. The lowest value of permeability that the bed rock is capable of offering is assumed to be 0 i.e. impermeable bed rock.

2.4 Soil Properties

On observing geotechnical investigations in some case studies[15, 16, 12] of landslides in Nepal, most slopes were found to be composed of higher sand, silt and gravel content with very little or no clay. A silty sand soil type with typical value of shear strength parameters[17, 18] and unit weight[19] was thus assumed for the purpose of this study.

Table 1: Model soil properties

Parameter	Cohesion	Angle of friction	Unit weight
Value	7	33.5	20.5
Unit	kPa	Degree	kN/m^3

The default function of Hydraulic conductivity and Volumetric water content from GeoStudio 2004 were selected for silty sand to include the variation of permeability and volumetric water content with respect to suction pressure, in the transient analyses. The functions are shown in Figure 1 and 2.

3. Methodology of Analysis

Sensitivity analysis is a process to assess the dependency of output parameters with various input

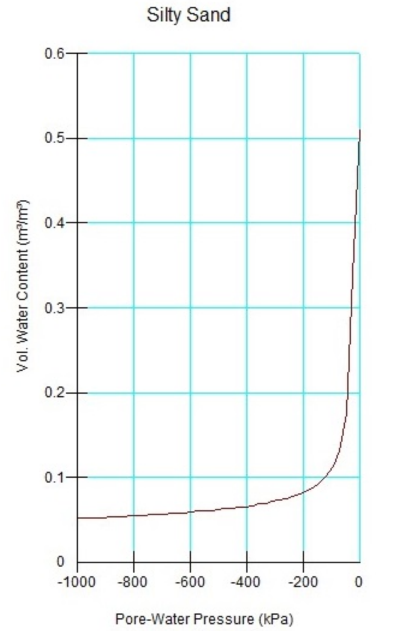

Figure 1: Volumetric water content function for silty sand

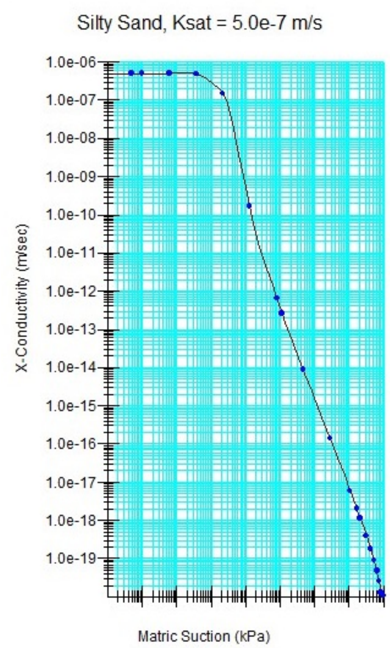

Figure 2: Hydraulic conductivity function for silty sand

parameters. During sensitivity analysis, the input parameter under consideration is varied keeping all other parameters constant and its relationship with output parameter is analyzed. To perform such actions, a range of values for each parameter is required. Based on observation of literatures on landslides[10, 11, 12], the length of slope is varied within the limits of 20m to 120m with an average value of 70m.
However, rainfall threshold unlike factor of safety has a definite value only in cases where initiation of landslide is actually possible i.e. where there is a possibility of factor of safety getting lower than 1. In a gentler slopes, even if the soil is fully saturated through rainfall, the factor of safety could be well above 1, hence there is no possibility of such landslide triggering intensity. On the other hand, if a very steep model is created, it is already unstable and there is no point of finding an intensity of rainfall that creates instability. Such is the case with soil depth also. Very shallow soil depth may not be able to generate landslide triggering forces due to low mass even after being fully saturated. But slopes of greater soil depths with low ground water table may not be able to increase its saturation as a consequence of high matric suctions, reduced permeability and increased shear strength. Therefore, the range of parameters for sensitivity analysis cannot be taken randomly. The possibility of failure has to be positive within ranges of each parameters. Trials were carried out to find these ranges of parameters within which definite values of threshold rainfall could be achieved.

3.1 Trials for Parametric Range

To start the trial, a mean depth of 3m was first assumed and critical angle required for initiation of landslide using full saturation was investigated for a 70m long slope. It was found that below the angle of 24 degree, landslide did not occur even at full saturation. The angle where even in dry condition the slope was not stable was also investigated, which was found to be angle above 42 degrees. So using a depth of 3m, length of 70m and mean angle of 33 degree the range of permeability of bed rock was also investigated. The maximum value of permeability offered by bed rock that could cause landslide was investigated using an maximum rainfall recorded in Nepal of 540mm/day[3] in simulation. This was done because drainage from the soil depends on permeability of bed rock and for higher values of the permeability of bed rock greater rainfall is required to saturate the soil.This maximum value of permeability of bed rock was found to be $1.5x10^{-7}$m/s. Now using the average values of ranges of angle, length and permeability of bed rock, the range of depth within which, instability could occur by rainfall was investigated. This was found to be between 2 to 3.5m. Below 2m depth, even full saturation could not decrease the factor of safety to less than 1. Above the 3.5m value of depth, the loss of negative pore pressure needed for sliding condition could not occur. Now the average depth was changed to 2.75m and new trial was carried out.
The mean depth of soil was now taken as 2.75m, and similar trials were carried out until the solutions converged. The finalized parameters with possibility of failure is shown in Table 2.

Table 2: Finalized Parameters for Sensitivity Analysis

Parameters	Mean value	Minimum value	Maximum Value	Unit
Slope Angle	34.5	29	40	degree
Slope length	70	20	120	m
Soil thickness	2.75	2	3.5	m
Permeability of Bed rock	9.35E-08	0	1.87E-07	m/s

3.2 Sensitivity Analysis

Sensitivity analysis was performed by varying the parameters one at a time and keeping the remaining parameters at arithmetic mean of their respective range. Two equal changes in both directions of the mean values of each parameters were considered. Rainfall thresholds were taken as the intensities of rainfalls that brought the factor of safety just below 1. The effects of changes in input parameters on the changes in rainfall thresholds of 1 day were observed. The average 1 day rainfall threshold was interpreted as threshold value given by the model with parameters at mean value.

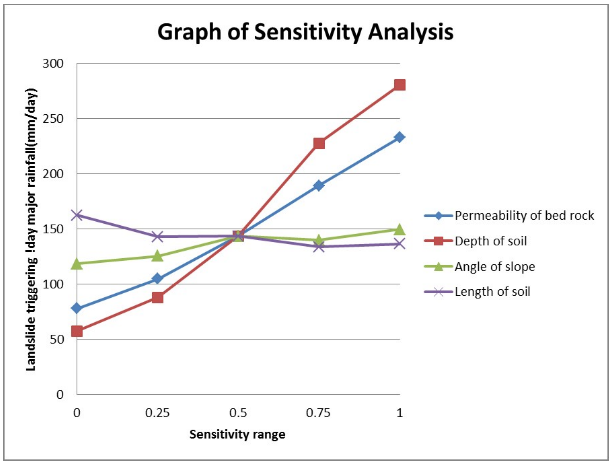

Figure 3: Result of Sensitivity Analysis

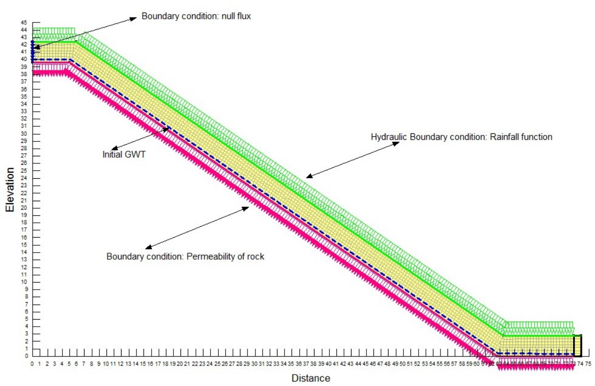

Figure 4: GeoStudio SEEP/W Model with Parameters at mean value

3.3 Intensity-Duration Relationship of Average Rainfall Threshold

The major rainfall durations were changed in the model having parameters at mean value and change in intensity of average threshold rainfall with its duration was observed. An intensity-duration relationship was then found by regression with a reasonable correlation coefficient of 0.9719.

4. Results and Discussions

The rainfall needed to trigger landslide increased with increase in soil depth. The rainfall threshold also increased with increase in Angle of slope and permeability of bed rock. But, with increase in length of slope the rainfall required to create instability decreased.

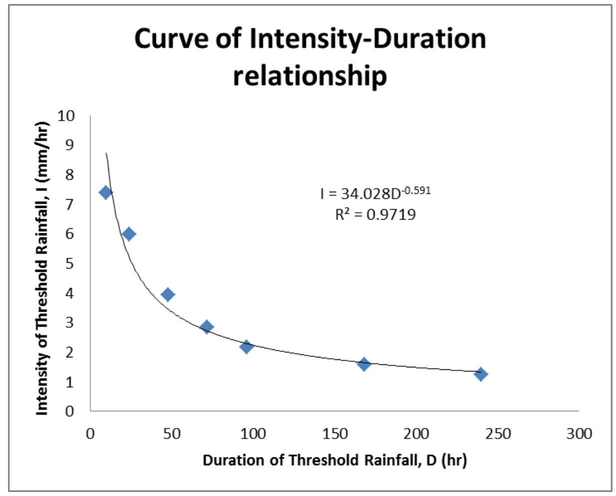

Figure 5: Curve of Intensity-Duration Relationship of Threshold Rainfall

Among all the parameters studied in this paper, the threshold rainfall was most dependent on the depth of soil. The slope of shallow soil cover with possibility of landslide initiation failed under much lower intensity of rainfall than greater soil depths. Permeability of bed rock was the next important parameter. The rainfall threshold value was least dependent on the length of slope followed by the angle of slope.

When compared to the empirically obtained rainfall threshold for Nepal Himalaya from a separate research[14], the results were very close. From this previous empirically obtained Intensity-Duration relationship for Nepal Himalaya[14], a threshold value of 144.04 mm/day was calculated for a duration of single day, while the average threshold rainfall of single day duration obtained by numerical modeling in this research was a rainfall intensity of 143.7 mm/day. Comparisons are shown between the two studies in Figure 6 and 7.

After regression the following relationship between intensity and duration of average rainfall threshold was obtained

$$I = 34.028D^{-0.591}$$

where, I is the intensity in mm/h and D is the duration in h.

The relationship was obtained with a power regression, and the change in rainfall threshold value decreases with the increase in duration of rainfall.

The results obtained in this paper are based on the assumptions that failure occurs within the soil mass only and no rock mass movement occurs. Hence, the applicability of Intensity duration relationship is limited to soil failures. Furthermore, the regression is done for duration starting from 10 hr up to 10days. So, the relationship can only be used within this range.

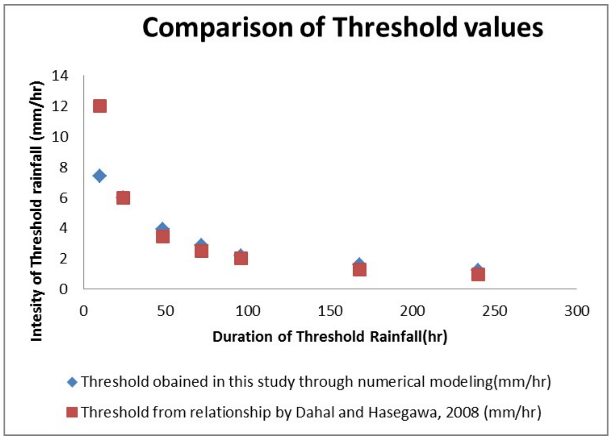

Figure 6: Comparison of Threshold output

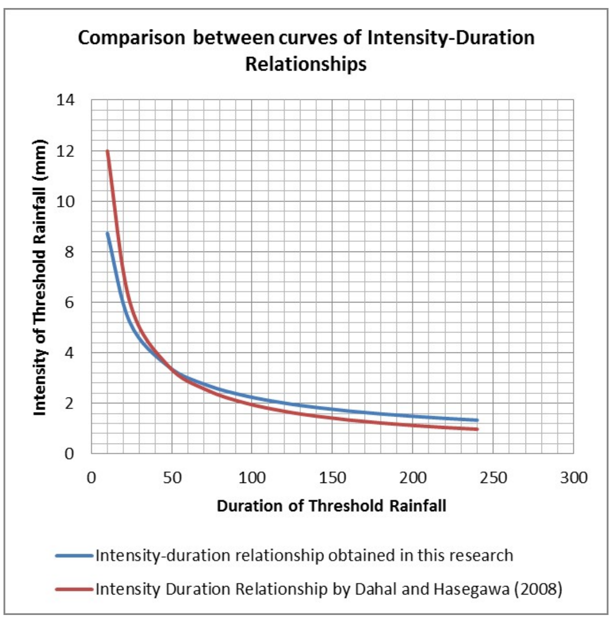

Figure 7: Comparison between curves of Intensity-Duration relationship

5. Conclusion

As seen from the comparison of results, the nature of association between duration and intensity of threshold rainfall, observed from the empirically formulated relationship is very similar to that obtained from numerical simulations. It can thus be said that, the Intensity-duration relationship of rainfall thresholds for areas of different soil types and geology can be successfully achieved with reasonably high accuracy through numerical modeling. For the selected soil type and parameters in this study, slope angles higher than a critical angle of 29 degree were seen as vulnerable to landslide under threshold rainfall. With varying combinations of different parameters, it was observed that a wide range of landslide triggering intensities of rainfall was possible in Nepal. For the worst possible combination of controlling parameters, even a 24hr rainfall of about 55mm/day could create landslide. Whereas, under favorable conditions, a 24hr rainfall as high as 280mm/day may be required to create landslide in a single day.

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