Synopsis of the Thesis

LOCAL AND REGIONAL SCALE LANDSLIDE HAZARD ANALYSES OF GUWAHATI CITY, INDIA

Submitted in the Partial Fulfilment of the Requirements for the Degree of

Doctor of Philosophy

by

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SYNOPSIS

Most landslides are a consequence of some particular rainfall events that induce instability to an otherwise stable slope. Though the rainfall-induced landslide are predominantly shallow soil slips of limited size, rapid velocity of such slides and their association with anthropic establishment make these failures highly hazardous and capable of causing unprecedented casualties. North-east (NE) India, being a seismically active zone, with a subtropical climatic condition and consequential torrential rainfall, presents one of the most favorable conditions for causing and triggering of landslides. Numerous examples can be cited for the rainfall-induced landslides in the North-eastern region of the country (Kalita, 2001), where it has resulted in tremendous loss of life and economy worth millions of rupees (ASDMA 2011, GSI 2013; Bhusan *et al*., 2014).

Several studies can be found in literature presenting the rainfall-induced slope stability analysis considering different rainfall-intensity-duration scenarios (Kim *et. al*. 2004; Huat *et al*., 2006) and antecedent conditions (Gasmo *et al*., 2000; Tsaparas *et al*., 2002; Tofani *et al*., 2006; Rahardjo *et al*., 2007). The available researches highlighted the importance of unsaturated soil characteristics to explain the phenomenon of rainfall induced slope stability/instability. The combined effect of the rainfall characteristics (intensity and duration) and the unsaturated soil characteristics, (vis., soil water characteristic curve (SWCC) and the unsaturated hydraulic conductivity curve (UHCC)) on the rainwater infiltration and landslide triggering mechanism have been studied and presented in detail (Fredlund, 1940; Bear, 1979; Anderson and Richards, 1987; Ng *et al*., 2001, Zhan *et al*., 2007; Rahimi *et al*., 2010; Wesley, 2010; Lu and Godt, 2013, Zhang *et al*., 2015).

Landslide analysis approaches can broadly be categorized into the local scale models focusing on single landslide process and the regional scale models focusing on landslide phenomena across greater spatial extent (Crozier and Glade 2005). The variability in geotechnical properties is a well-established fact, which primarily arises out of depositional and post-depositional, geological and geomorphological processes (Lee et al. 1983; Lacasse and Nadim, 1996; Baecher and Christian, 2003). Slope stability analysis has always been compliant to probabilistic treatment and due attention towards this approach is highlighted in the literature (Alonso, 1976; Vanmarcke, 1977a&b; Cho, 2007).

Several studies can be found in literature presenting the problem of rainfall-induced landslides within a Geographic Information System (GIS) framework and subsequently formulating methodologies to quantify landslide susceptibility and landslide hazard. Within a GIS framework, the in-situ conditions and mechanical properties of the potentially sliding soil mass are taken into account to develop physically based models (analytical) for regional scale landslide studies. TRIGRS (Transient Rainfall Infiltration and Grid based Regional Slope-stability), combined with a simple runoff routing scheme, is one such method which is widely used due to its ability of computing transient pore-pressure changes and changes in the factor of safety due to rainfall infiltration (Baum et al., 2002; Savage et al., 2004, Salciarini *et al*., 2006; Salciarini *et al*., 2008; Sorbino *et al*., 2010; Kim *et al*., 2010; Park *et al*., 2013; Saadatkhah *et al*., 2014; Schilirò *et al*., 2015).

The extensive literature review indicates the necessity to conduct both the regional and local scale landslide studies in unison to decipher the failure probabilities of landslide in a global scale as well as in the localized vulnerable spots. In this context, the objective of the present study is set to investigate the rainfall induced landslides in both local and regional scale levels. To meet this objective, Guwahati region and its hillslopes is adopted as the study area. Soil samples were obtained from different hill slopes and are characterized for their different index and engineering properties necessary for landslide analyses. Local scale and regional scale level analyses were performed considering the rainfall data obtained for the study area. Local scale analyses were conducted with finite element/difference and limit equilibrium methods, using GeoSlope and FLAC software. Regional scale analyses were performed with application of TRIGRS in the GIS framework. Deterministic and probabilistic analyses were conducted which provided the Factor of safety (FoS) and Probability of Failure (PoF) maps for highlighting the landslide hazard of the study area. The complete work carried out for this study is presented in nine chapters which are briefly outlined in the following sections of the report.

Chapter 1 presents the introduction to the problem, background, and broad objective, of the research work along with the organization of the thesis.

Chapter 2 provides a detailed review of literature pertinent to the slope stability analysis of rainfall-induced slope failure, probabilistic slope stability analysis, and regional-scale physically based landslide analysis methods within the GIS framework. The chapter concludes with a critical appraisal of literature and a detailed scope of the work.

Chapter 3 presents the details of the study area and methodology adopted for the study. The geomorphology, geology, climate and rainfall pattern, and the geological features of the Guwahati region are briefly discussed. Rapid Visual Screening (RVS) observations for potential landslide areas of Guwahati region (Goswami, 2013), superimposed on the study area, are shown in Figure 1. **Figure 2** shows the typical rainfall data (1998 – 2015) collected for the study area. **Figure 3** indicates the methodology adopted for the study, which involves local scale and regional scale analyses, based on the collected rainfall data and the properties of the soils determined from laboratory and field experiments.

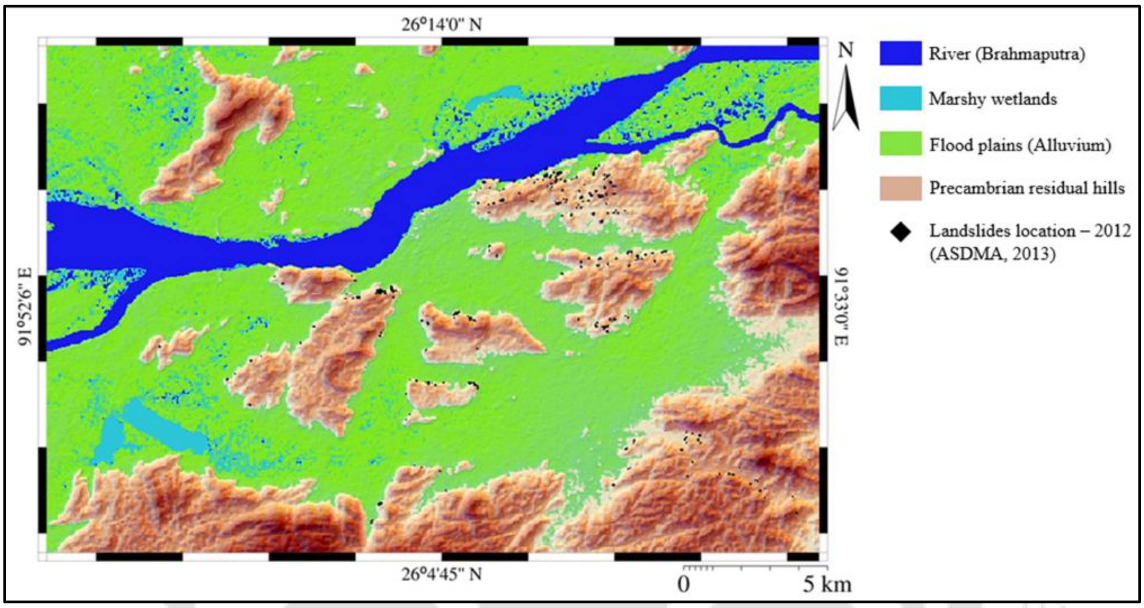


Figure 1 Study area along with the RVS locations

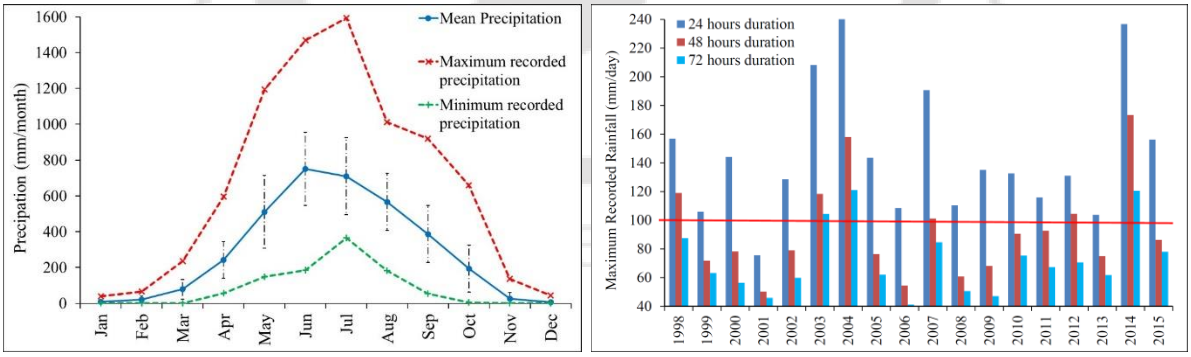


Figure 2 (a) Monthly mean rainfall (for a period of 1901 – 2002) in the district of Kamrup (b) Maximum rainfall intensity for the period 1998 – 2015

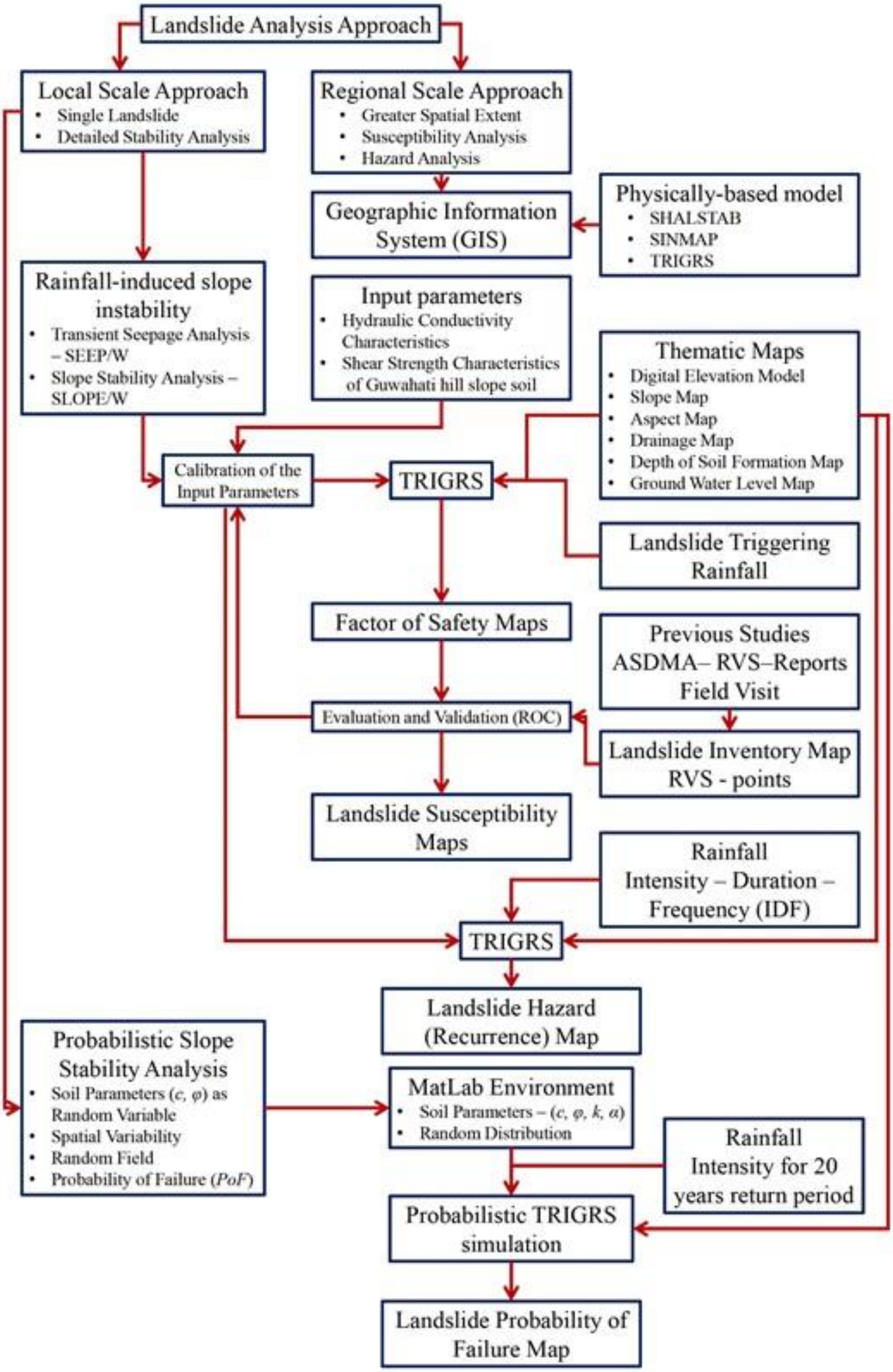


Figure 3 Methodology adopted for the present study

Chapter 4 discusses about the geotechnical characterization of the hill slope soils of the study region. Laboratory tests were performed on disturbed and undisturbed soil samples to assess the geotechnical characteristics including Soil Water Characteristic Curve (SWCC). Representative in-situ infiltration properties of the soils, at selected site locations, were determined using Mini-disk infiltrometer and Guelph Permeameter. **Figure 4**(a) depicts the grain size distribution (GSD) curve of the two types of typical hillslope soils of the study area. **Figure 4** (b) shows the typical results of triaxial tests on the saprolitic soil (Soil-1). Table 1 gives the summary of the properties of tested soils. **Figure 5** typically depicts the SWCC, relation between the volumetric water content (θ) and the matric suction (ψ) for Soil -1. For describing the SWCC to be used in the numerical simulations, Van Genuchten (1980) model is fitted to the obtained experimental data.

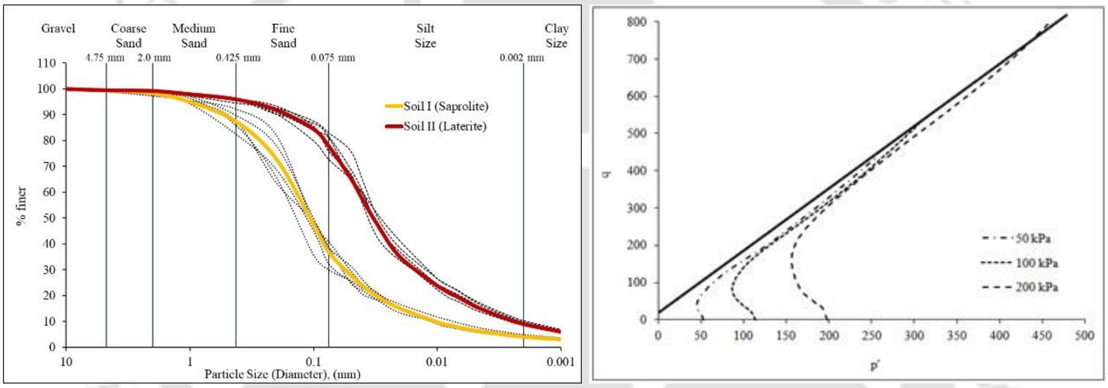


Figure 4 (a) GSD of the hill slope soils (b) *p*'-*q* plot exhibiting CU triaxial test on Soil-1

Table 1 Summary of the properties of the regional soils

<table>
<tr><th rowspan="2">Soil Characteristics</th><th rowspan="2">SOIL 1 – Laterite – Silty Clay</th><th colspan="2" rowspan="2">SOIL 2 – Saprolite – Silty Sand</th></tr>
<tr></tr>
<tr><td>Specific gravity</td><td>2.68</td><td colspan="2">2.68</td></tr>
<tr><td>In-situ dry density (g/cm)</td><td>1.50</td><td colspan="2">1.57</td></tr>
<tr><td>Liquid limit (%)</td><td>47</td><td colspan="2">35</td></tr>
<tr><td>Plastic Limit (%)</td><td>27</td><td colspan="2">Non – plastic</td></tr>
<tr><td>Fines content (%)</td><td>77.8</td><td colspan="2">36.75</td></tr>
<tr><td>Porosity</td><td>0.44</td><td colspan="2">0.41</td></tr>
<tr><td>In-situ degree of saturation (%)</td><td>95</td><td colspan="2">47.79</td></tr>
<tr><td>Saturated permeability</td><td>10^{-6} m/s</td><td colspan="2">10^{-5} m/s</td></tr>
<tr><td rowspan="2">Mohr-Coulomb shear strength parameters</td><td rowspan="2"></td><td>c'</td><td>φ'</td></tr>
<tr><td>5–15 (kPa)</td><td>25^{o}-31^{o}</td></tr>
</table>

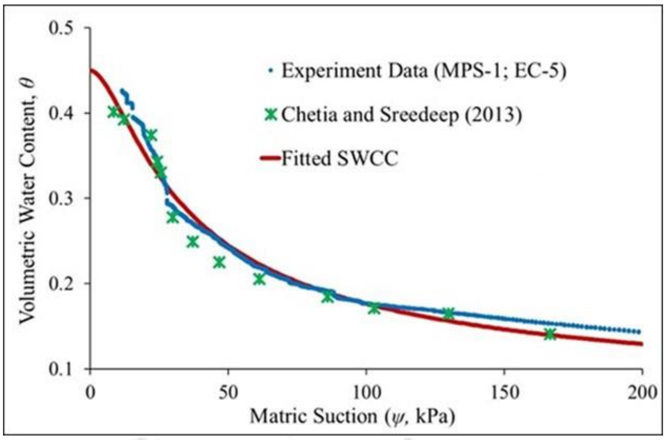
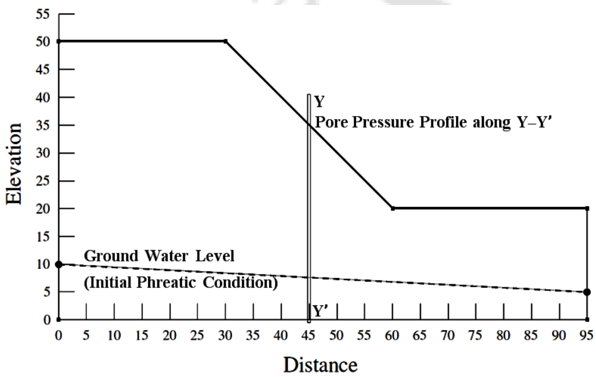


Figure 5 Soil water characteristics curve of Soil-1 available in Guwahati hillslopes

Chapter 5 discusses the local scale analysis of rainfall-induced slope stability. The changes in water content and matric suction, in response to rainfall infiltration, and their effect on the slope stability is analyzed through numerical modelling. Seepage analysis is performed using SEEP/W (Geo-Slope, 2007) for transient/steady state conditions considering saturated / unsaturated material model and the computed pore-water pressure are then used in SLOPE/W (Geo-Slope, 2007) to evaluate the changes in stability with time applying Limit Equilibrium (LE) method. Based on the relevant soil properties of the study area as reported in literature, the numerical investigation applies the unsaturated soil mechanics approach to explain the rainfall-induced landslides in the study region. **Figure 6** shows a typical slope geometry adopted for the study and the initial in-situ condition. **Figure 7**(a) shows the pore pressure change with rainwater infiltration within the slope, while **Figure 7**(b) shows the typical variation of factor of safety with time. The study highlights the influence of rainfall infiltration on the stability of slopes in a local scale.



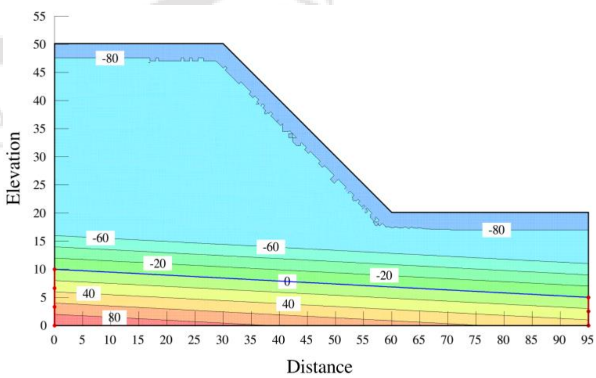


Figure 6 (a) Typical slope geometry (b) Initial in-situ pore pressure distribution

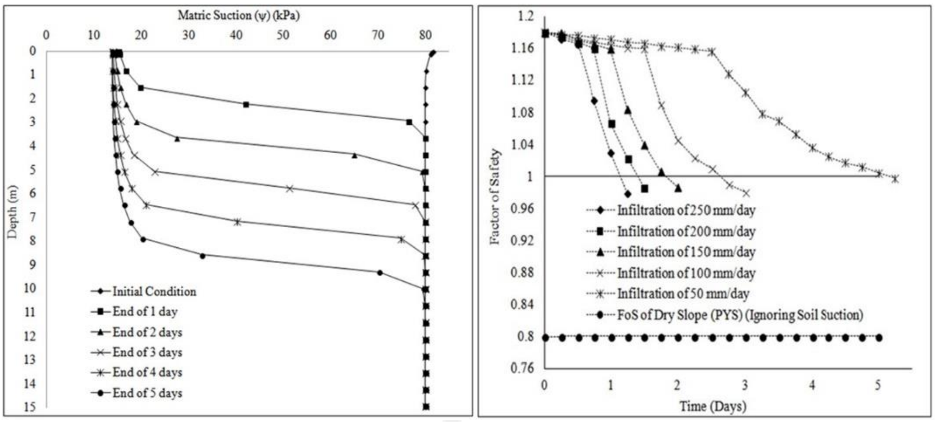


Figure 7 (a) Pore pressure profile with rainfall infiltration (b) Temporal variation of FoS for a typical slope composed of pale yellow silty sand (PYS) (Soil – 1)

The study highlights the importance of considering the unsaturated shear strength of soil in the analysis and prediction of the stability of unsaturated soil slopes. SWCC and unsaturated hydraulic conductivity of the soil, in combination with its unsaturated shear strength, play a very significant role in determining the potential of slope towards its failure. Hill slopes within the city of Guwahati are susceptible to rainfall-induced landsliding. Propensity of landsliding varies depending on the type of soil and its response to infiltration. Based on the coupling of transient seepage analysis (using the finite element method in SEEP/W) and subsequent slope stability analysis (using the limit equilibrium method in SLOPE/W), a predictive model for the rain-induced instability of the natural residual soil slopes is developed to estimate their degradation of stability and subsequent failure.

Probabilistic slope stability, considering the spatial variability of soil, is carried out to take in to account the variability of shear strength parameters within a soil slope. Based on an isotropic random field, **Figure 8**(a) and (b) shows a typical distribution of soil parameter within the soil mass. The variation of properties within the soil mass can be clearly observed with the change in correlation structure. **Figure 8**(c) shows the results obtained from the analysis for isotropic random field, revealing the increase in probability of failure with the increase in spatial correlation length. Beyond a specific correlation size, the probability of failure remains unaffected. This is attributed to the fact that with the increase in correlation length, the soil parameters tend to vary smoothly over large distances and larger zones of near valued parameters are formed. The study shows that depending on the spatial correlation structure, a slope, with a given factor of safety, can have different probability of failure, therefore associated with different risk levels. Thus, in comparison to factor of safety, the probability of failure is recognized as a better parameter to describe the stability condition of slope, as it takes into account the natural variability in geotechnical properties as well as the uncertainty in geotechnical analysis.

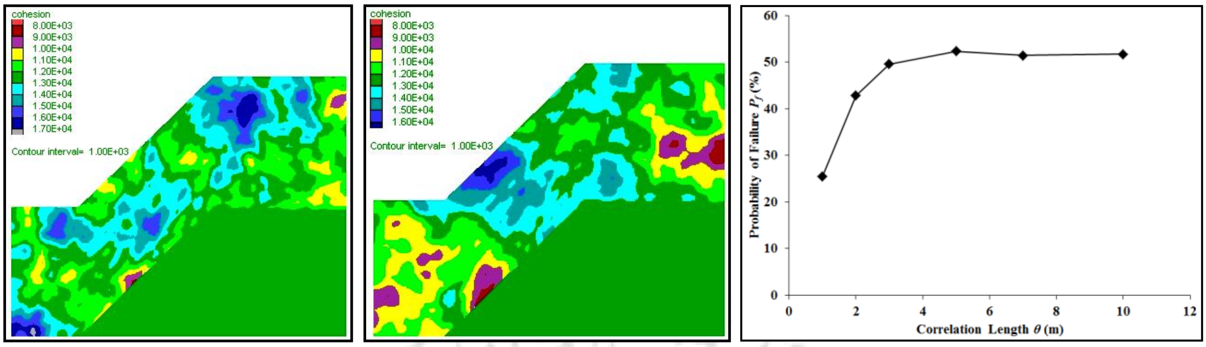


Figure 8 Isotropic random field for (a) $\theta_x = \theta_y = 5.0$ m and (b) $\theta_x = \theta_y = 10.0$ m; (c) Probability of Failure vs. Correlation Length for isotropic random field.

Chapter 6 discusses in detail about the physically based model, TRIGRS (Transient Rainfall Infiltration and Grid based Regional Slope-stability). TRIGRS is a FORTRAN code developed for evaluating the transient pore water pressure response to rainfall infiltration and simulate the temporal and spatial distribution of shallow rainfall-induced landslides, expressed as decrease in the factor of safety values (Baum *et al*., 2002; Savage *et al*., 2004; Baum *et al*., 2008). TRIGRS uses a simple infinite-slope model to compute the factor of safety (*FoS*) on a cell-by-cell basis on a GIS framework. Considering one-dimensional, vertical flow in isotropic, homogeneous materials for saturated or unsaturated conditions, the FoS is calculated for transient pore pressure head. TRIGRS provide the closest possible approximation of potential instability under the impact of rainfall infiltration for different rainfall scenarios (Baum *et al*., 2002). A meaningful outcome from TRIGRS is dependent on the input parameters representative of the study area. The input data required for TRIGRS simulation includes the Digital Elevation Model (DEM) of the study area (**Figure 9**a) and the derived aspect map, the slope map (**Figure 9**b), and the map representing the depth of basal-boundary (generated from the slope map). The input soil parameters include Mohr-Coulomb shear strength parameters (cohesion – c and angle of internal friction – φ), soil unit weight (γ), saturated hydraulic conductivity (k_s), saturated and residual volumetric water content (θ_s and θ_r) and soil diffusivity (D_o). The values of these parameters are determined through a parametric study involving a SEEP/W model (**Figure 10**a), along with TRIGRS simulation consisting of single representative cell and the FoS map output of the entire study area., The input are calibrated such that the values of these parameters fit within the range of the experimentally determined soil parameters, while the output FoS map is representing the in-situ scenario.

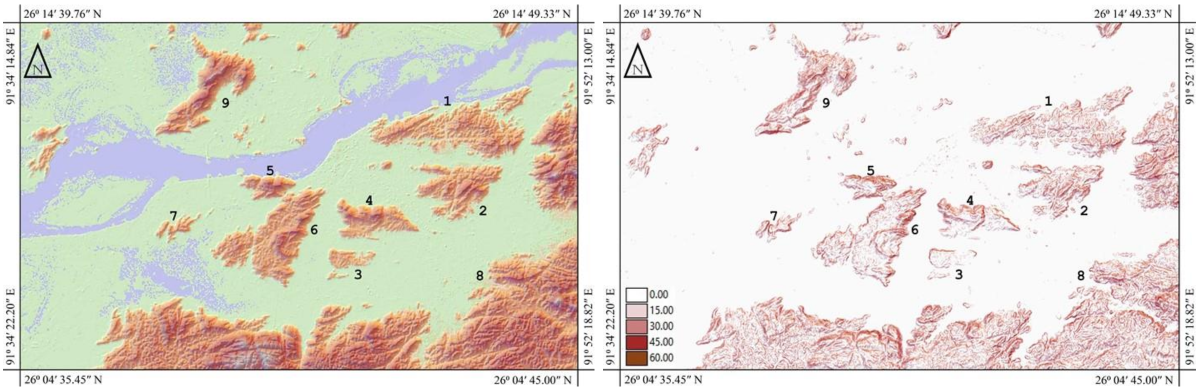


Figure 9 (a) Digital elevation model (DEM) and (b) Slope map (in degrees) of Guwahati city

The TRIGRS parameters are so considered that the temporal rise in water table is in close resemblance to that obtained from SEEP/W simulations. Emphasis is given on the time of occurrence and location of the initiation of slope failure due to the rising water table. The rise in water table is the triggering factor for slope failure as can be observed from **Figure 10**(b) and (c). **Table 2** gives the values of the soil parameters finalized for conducting the rainfall induced landslide hazard analysis of the study area.

The rainfall event of June 2012 triggered several landslides distributed across the hills of the Guwahati region. The location of landslide occurrences of June 2012 and other landslide prone sites were presented in the RVS-ASDMA report (Goswami, 2013) in the form of GPS Latitude-Longitude coordinates, overlaid on Google Earth Imagery. The areas delineated in the report were revisited in-situ and a total of 347 locations (GPS Lat-Long coordinates) are considered for this study. **Figure 11** highlights the locations (henceforth referred as RVS-points) overlaid on the TRIGRS *FoS*-maps for comparative analysis of the simulation results.

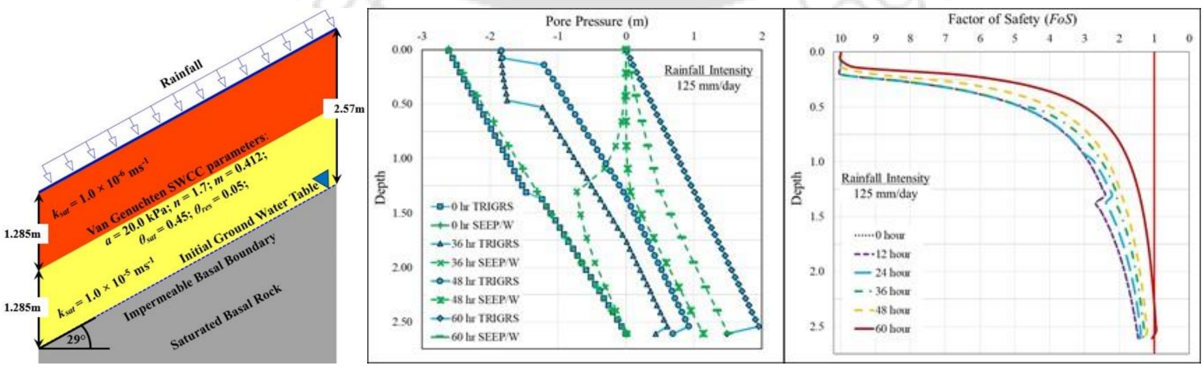


Figure 10 (a) Soil profile for SEEP/W analysis (b) Pore pressure and (c) Factor of safety profile from TRIGRS analysis for rainfall intensity of 125 mm/day

Table 2 Input parameters applied in the TRIGRS simulation based on parametric study

c' (kPa)	φ' (°)	γ_s (kN/m^3)	k_s (m/s)	D_o (m/s)	θ_s	θ_r	α
10	27°	18.5	2.5×10^{-6}	2.5×10^{-5}	0.45	0.05	0.8

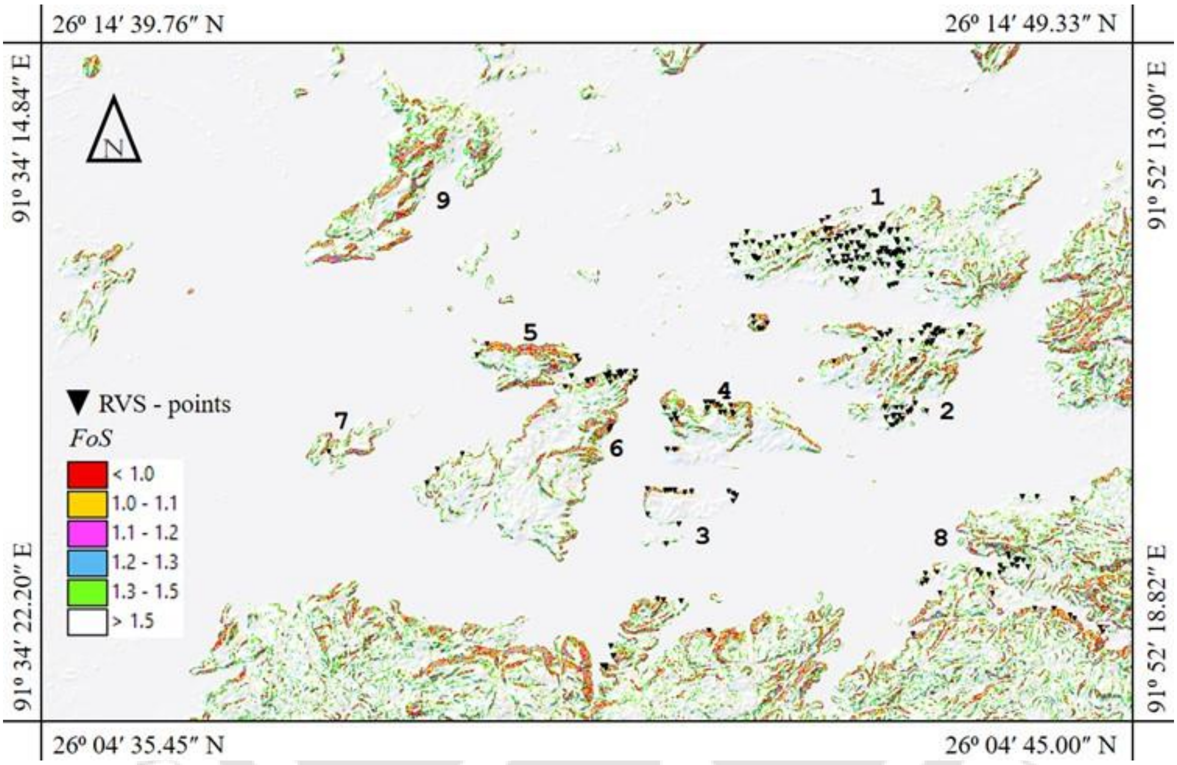


Figure 11 TRIGRS *FoS*-map for 25 June 2012 using ALOS-3D as base DEM with overlaid RVS-points

Chapter 7 discusses the application of TRIGRS to investigate the rainfall-induced landslide hazard scenarios for the Guwahati city. The study utilized various publicly available Digital Elevation Models and investigated their individual suitability for assessing the predictability of rainfall-induced landslide scenario of the Guwahati region. A total five DEMs are used for the study vis., CartoSat-DEM (CartoDEM - 1/3 and 1 arc sec), AW3D30-DEM (ALOS-3D), SRTM-DEM, ASTER-GDEM. **Figure 12** shows the difference in the response in terms of the FoS of the RVS-points against the daily rainfall when different DEMs are considered as the base map for the rainfall-induced landslide analysis.

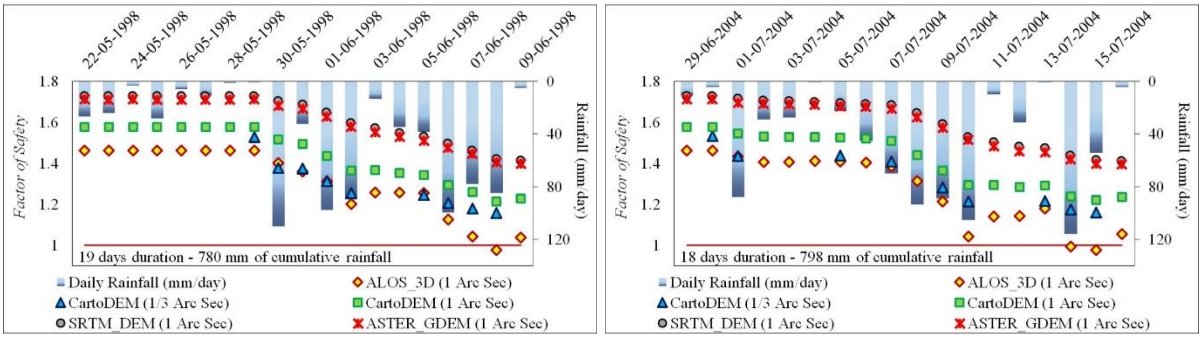


Figure 12 Average *FoS* of the RVS-points for rainfall event of (a) June, 2012 (b) July, 2004

The effectiveness of landslide predicting models, such as TRIGRS, are mostly evaluated based on a statistical classifier such as Receiver Operating Characteristics (ROC) using a confusion matrix (Godt *et al*., 2008; Montrasio *et al*., 2012; Raia *et al*., 2014). The ROC of the TRIGRS FoS–maps are calculated and plotted for the DEMs for a particular rainfall event and shown in **Figure 13**. The locations of landslides from the simulated scenarios using ALOS-3D DEM were in maximum agreement with the observed sliding locations. The study showed that the choice of DEM can make a significant impact on the results obtained from the TRIGRS simulations.

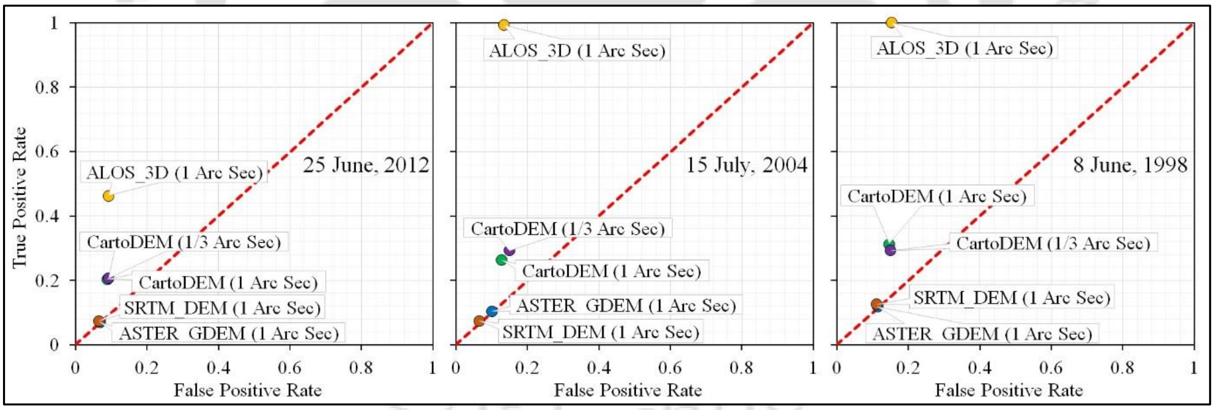


Figure 13 ROC for the TRIGRS simulation results

Rainfall events, which were reported to have triggered landslides in Guwahati city, are identified and further used as input into TRIGRS simulation. The rainfall intensity input is provided as daily (24-hour) time-steps and the corresponding response of the Factor of Safety (FoS) the region is obtained. The temporal dynamics of the FoS in response to rainfall over the rainfall duration is obtained and plotted. **Figure 14**(a) shows the rainfall for the month of June 2012 and the degradation of the FoS over the entire month. **Figure 14**(b) shows the analysis results for FoS in response to rainfall of March-April 2010. **Figure 15**(a) gives the analysis results of the rainfall event of June 1998. **Figure 15**(b) compares the rainfall of 2010 and 2012 and demarcates the rainfall event that was able to trigger landslides in the study area. The comparison highlights the intricate equilibrium of the antecedent rainfall or soil moisture condition, the intensity and duration of the triggering rainfall and the soil hydraulic properties.

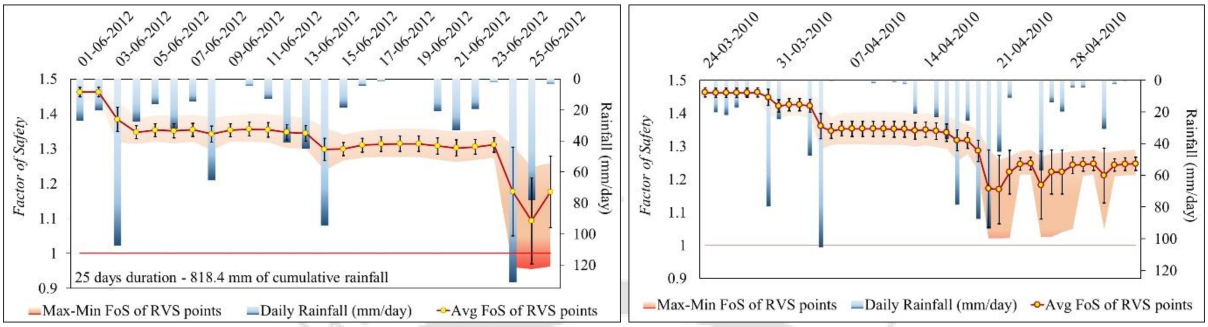


Figure 14 (a) Landslide triggering rainfall event of June 2012 (b) Rainfall of March-April 2010

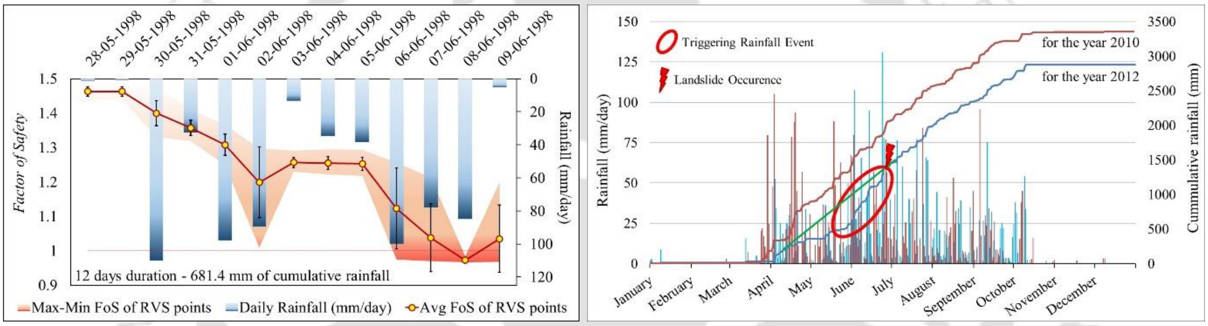


Figure 15 (a) Landslide triggering rainfall event of June 1998 (b) Comparison of 2010 and 2012 event

To check the effect of the rainfall pattern on the landslide triggering, two rainfall events reflecting the rainfall intensity and duration prevalent within the study region is assumed. **Error! Reference source not found. Figure 16** shows a cumulative rainfall of 400 mm distributed over 5 days, being applied in increasing intensity (RP-1), constant intensity over the duration (RP-2) and decreasing intensity (RP-3).

Figure 17 Error! Reference source not found.(a) shows the variation in actual rate of infiltration at the surface of the slope for RP-1, RP-2 and RP-3, and it can be observed the rate of infiltration is significantly affected by the rainfall intensity. **Figure 17 Error! Reference source not found.**(b) shows the development of pore pressure and the reduction of FoS with time as a response to rainfall RP-1, RP-2 and RP-3. It can be observed that the trend in rise in the pore water pressure is analogous to the increase in the hydraulic conductivity and a mirror image to the FoS. It can be understood that it is the pore water pressure rising beyond a certain threshold value that ultimately triggers the sliding of the soil mass.

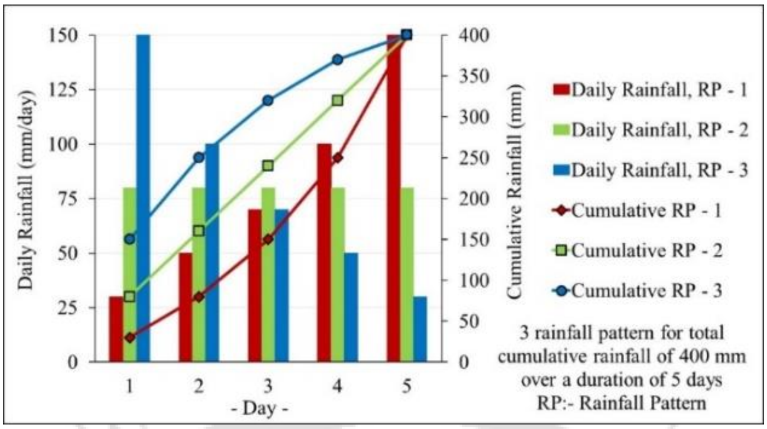


Figure 16 Rainfall pattern for cumulative rainfall of 400 mm distributed over 5 days

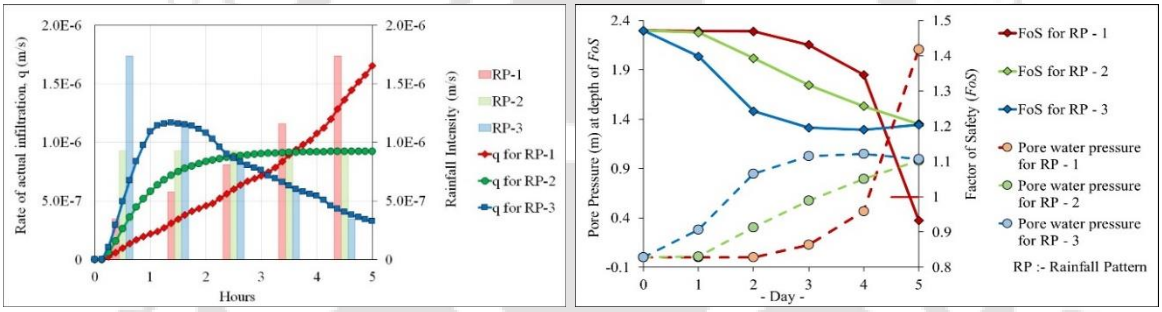


Figure 17 (a) Actual rate of infiltration through slope surface and (b) Pore water pressure and FoS at basal (sliding) interface for RP-1, RP-2 and RP-3

Figure 18**Error! Reference source not found.** shows the degradation in the stability condition of the slope, in the form of decreasing FoS as a response to RP-1, RP-2 and RP-3. The FoS shown in the figure**Error! Reference source not found.** represents an average value across all the RVS point locations or cells. The average FoS drops below 1.0 indicating widespread landsliding for the rainfall event depicting increasing rainfall intensity RP-1. With time, the saturation of the soil increases, and so does the permeability along with the rainfall intensity, thus allowing more water infiltration into the soil slope. The loss of rainwater, as runoff, has been the minimum, and therefore the ground water table rises to such a level to be able to trigger widespread landslide.

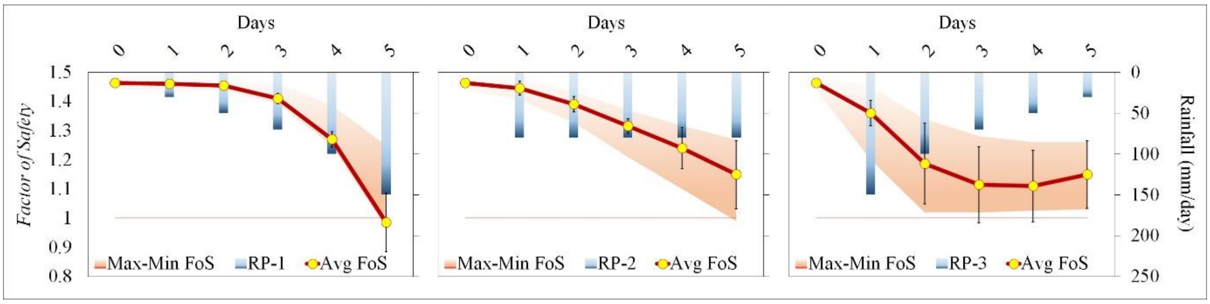


Figure 18 *FoS* of the RVS points as response to rainfall event RP-1, RP-2 and RP-3

To quantify landslide hazard, the rainfall intensity – duration – frequency (IDF) relationship is evaluated. **Figure 19**(a) depicts the IDF curves for the Guwahati city region. Forty-nine (7-rainfall durations for 7-rainfall return periods) rainfall scenarios (**Figure 19**b) were taken into consideration to represent the most probable rainfall intensity – durations corresponding to return periods. The rainfall intensities were provided as input into TRIGRS and the FoS maps were obtained. The landslide hazard was thus evaluated considering the return period of the rainfall event triggering landslides.

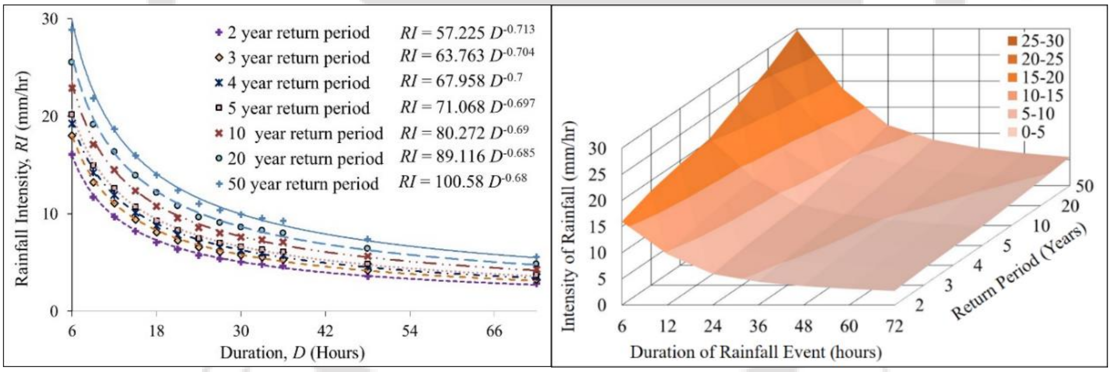


Figure 19 (a) Rainfall Intensity–Duration–Frequency (IDF) curve for Guwahati region (b) Rainfall intensity corresponding to return period and rainfall duration selected for the study

The FoS maps are subsequently combined to develop the landslide hazard map, which gives the location of probable landsliding in terms of return period. Figure 20 depicts the return period of rainfall induced landslide occurrences or the Landslide Hazard Map of Guwahati city.

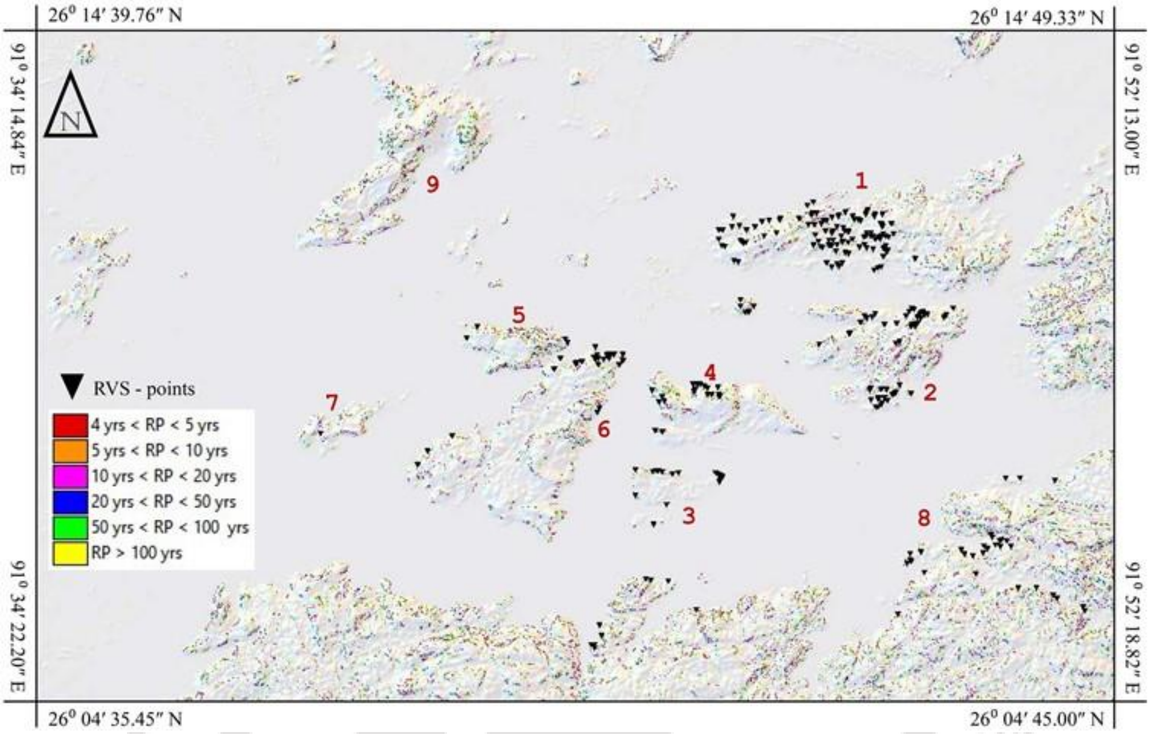


Figure 20 Landslide hazard map of Guwahati city based on varying return period

Chapter 8 discusses the application of TRIGRS for probabilistic slope stability and generate Probability of Failure (PoF) maps instead of the FoS map. The input parameters, namely cohesion, internal friction angle, saturated permeability and the α-parameter (Gardner, 1958), are considered as random variables as it would be in nature. MatLab codes were developed to generate the random distribution of the input parameters, use the same run TRIGRS simlations from MatLab (one set at a time for typically 10000 number of simulations), and generate and save the FoS maps. Thus, at the end of the simulation, typically 10000 number of FoS maps are generated. The maps are read by another MatLab code, which counts the number of times the FoS drops below 1.0 at a particular location or cell and calculates the PoF, thereby generating the PoF maps. **Figure 21** gives the distribution of cohesion and angle of internal friction as a histogram plot. **Figure 22**(a) gives the correlation between the cohesion and angle of internal friction. **Figure 22**(b) shows a typical PoF map of the study area.

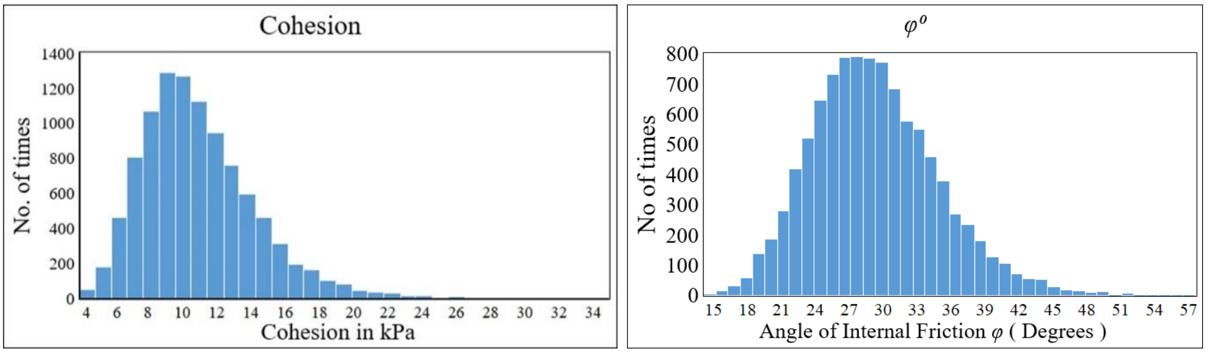


Figure 21 Probability distribution of (a) cohesion and (b) angle of internal friction considered in the study

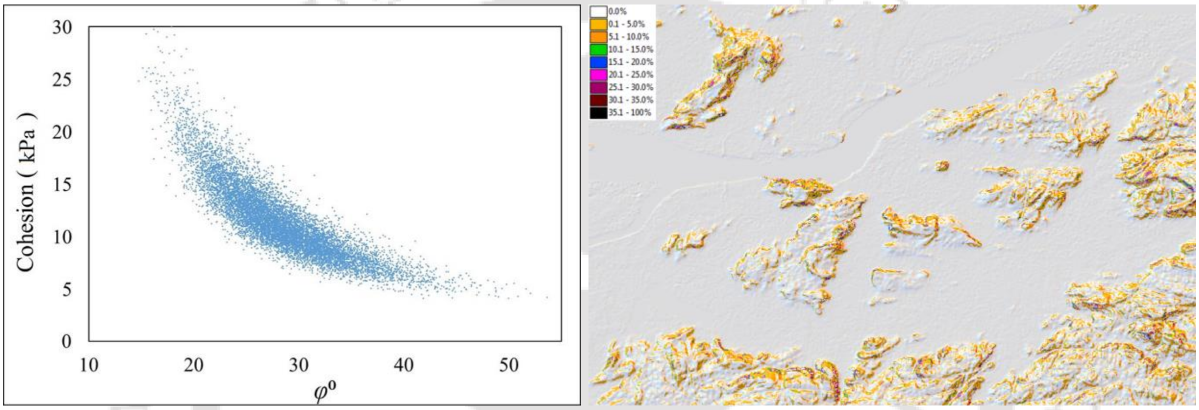


Figure 22 (a) Cross-correlation of cohesion and angle of internal friction (b) A typical PoF map of Guwahati City

Chapter 9 provides the summary of the thesis and conclusions drawn from the present research. The limitations of the present work are presented along with the future scope. The major conclusions of the work are listed below.

1. The hill slope soils of Guwahati city are formed based on in-situ weathering. The geological stratification characterizes progressive stages of residual weathering, typical of tropical and sub–tropical climatic conditions.
2. The geology of the study region is an extension of the Shillong Plateau. The basal rock types and the overburden residual soil profile were found to be similar with typically two types of soil, namely the top reddish silty clay / laterite and bottom silty sand / saprolite.
3. The saprolite formation is very porous and friable in nature and can easily crumble from the slightest disturbance, and is highly susceptible to landsliding.

4. Slope analysis, applying conventional soil mechanics and ignoring unsaturated soil behavior, gives an unrealistic estimate of the stability condition and fails to explain the rainfall induced slope failure mechanism.
5. Slopes within the city of Guwahati have the potential of undergoing rainfall-induced landsliding, and the potential will vary depending on the type of soil and its response to infiltration.
6. Slope with a given factor of safety can have different probability of failure depending on the random distribution of the soil properties, and therefore will be associated with different risk levels.
7. A model for predicting the soil depth or the depth of basal boundary was considered based on in-situ data.
8. The study showed the Digital Elevation Model (DEM) have a significant impact on the results obtained from the TRIGRS simulation. The DEM should be representative of the topography of the study area. The ALOS-3D DEM has a better agreement between the simulated scenario and the in-situ locations.
9. The simulation output as Factor of Safety map is validated based on a statistical classifier such as Receiver Operating Characteristics (ROC) using confusion matrix, aided by the observations as RVS points. TRIGRS has been able to simulate the landslide occurrence within the Guwahati hill slopes.
10. The study showed that for landslide triggering in Guwahati, the antecedent condition plays a significant role. The shorter duration rainfall (event spanning less than 36 hours, with dry period on either side) was not sufficient to cause landsliding.
11. A minimum duration of 48 hours rainfall, with intensity of 100 mm/day, can be considered as a threshold sufficient enough to trigger landslide in Guwahati hill slopes.
12. The study showed the significant impact of the rainfall pattern, along with the rainfall intensity-duration relation. The total infiltration is the maximum for rainfall event with increasing rainfall intensity over the duration.
13. The intricate combination of the antecedent rainfall over sufficient duration and triggering rainfall ultimately leads to landsliding.
14. The rainfall Intensity – Duration – Frequency (IDF) for the Guwahati region were evaluated for input into TRIGRS for the assessment of landslide hazard of the study area. The outputs were combined into a Landslide Hazard Map of the Guwahati region.

15. To account for the natural variability of the soil parameters, the TRIGRS input parameter were considered as random variable over a range of values for probabilistic analysis and the Probability of Failure (PoF) map is generated from the analysis.
16. The methodology developed and presented herein for the study of landslide hazard scenario of Guwahati city can be effectively used for other such regions prone to rainfall induced landslide calamities.

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