Chapter 23
Dynamic Stability and Landslide Simulations in Hilly Regions of Kerala

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Introduction

The recently occurred landslides in the hillside regions of Kerala cause severe damages to civil infrastructures and the death of human beings. The intensity of landslides kept rising when humankind activities of unscientific quarrying, road expansion, and big infrastructure projects are carried out in these regions. The change in the rhythm of the monsoon is also an added factor. High intense rainfall leads to the most disastrous fluidized landslides, which usually occur very unexpectedly. Landslides become severe with dynamic activities of continuous vibrations due to constant heavy traffic movements, mining activities, and industrial machine operations in addition to excess rainfall intensity. Kerala is known for its low seismic history. But, the effects of excavation of building stones through blasting with explosives are high on landslide movement in the hilly regions. Since the natural formations and boulders in these locations are prone to rockfall and landslides, it is essential to study the dynamic stability of the slopes. The present paper aims to model landslide movement triggered by rainfall intensity and minor seismic amplitude at a few existing soil slopes of Kerala using integrated landslide simulation model LS Rapid software. Since the average pore pressure ratio represents the rainfall intensity, the pore pressure ratios are varied from 0.1 to 0.9 to study the effect of rainfall intensity on landside stability. Further, the slopes are subjected to low seismic amplitude to represent the influence of minor dynamic loading conditions. It also examined the effect of soil properties on landslide stability.

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K. Muthukumara et al. (eds.), *Earth Retaining Structures and Stability Analysis*,
Lecture Notes in Civil Engineering 303,
https://doi.org/10.1007/978-981-19-7245-4_23

Characterization of Soil Slopes

Integrated Landslide Simulation Model—LS Rapid

LS Rapid is computer simulation model software that integrates the initiation process to the rapid landslide motion triggered by rainfall and earthquake. It may be due to strength reduction and the entrainment of deposits in the run-out path [1]. The available stability analysis methods based on LEM used to analyze the soil slopes assume that the sliding mass fails only once. But, in actual landslides, the regions subjected to high pore pressures fail first, followed by expansion of the failure area around the initial failure zone. Eventually, the whole landslide mass will start to move. LS Rapid software simulations can reproduce such progressive failure phenomenon. The basic concept of the LS Rapid model is rooted in establishing an imaginary vertical column within the moving landslide mass. The forces acting on the soil column shown in Fig. 23.1 are including self-weight of the soil column (W), horizontal seismic forces in X and Y directions (F_x and F_y), vertical seismic force (F_v), and lateral earth pressure acting on the walls (P), shear resistance acting on the bottom of the column (R), normal stress acting at the bottom (N) and pore pressure acting on the bottom (U). The component of self-weight parallel to the slope, shear resistance, and sum of the balance of lateral earth pressures in X and Y directions can cause the landslide mass to slide downward.

The landslide mass (m) is accelerated by acceleration (a) generated by the total forces acting on the vertical soil column. It is denoted as:

$$am = \left(W + F_v + F_x + F_y\right) + \left(\frac{\partial P_x}{\partial x}\Delta x + \frac{\partial P_y}{\partial y}\Delta y\right) + R \qquad (23.1)$$

where R includes the effect of normal stress and pore pressure acting on the bottom of the soil column. All the stresses and displacements are calculated by projecting into a horizontal plane.

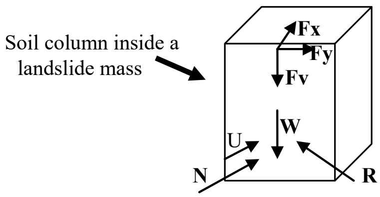

Fig. 23.1 Soil column element within a moving landslide mass

Table 23.1 Location and geometrical details of the soil slopes

Location	Slope angle (°)	Slope height (m)	Latitude	Longitude
Aadit, Idukki	41.96	950	N10°1′15″	E77°2′48.8″
Kallar, Idukki	44.23	1140	N10°02′25.3″	E77°00′19.9″
Mavadi, Idukki	44.6	1058	N9°52′09.1″	E77°07′46.5″
Kakkattuppara, Wayanad	45	490	N11°25′42.3″	E76°20′45.7″
Kavalappara, Wayanad	35	275	N11°24′43.2″	E76°14′13.92″
Mananthavadi, Wayanad	52	924	N11°50′36″	E75°58′51″
Puvaramthodu, Wayanad	41	1281	N11°22′47.5″	E76°18′44.5″

Geometrical Features of the Slopes

For the present study, three slopes from the Idukki district and four from the Wayanad district of Kerala have opted. All the slopes selected are located near to previously occurred landslides. The slope angles of the chosen locations are found to be greater than 30°. Table 23.1 gives the site of the place and geometrical features of the slopes.

Creation of Topography

ArcGIS software and LS Rapid software of version 2.1 have been used to create the topographies of the soil slopes. The digital elevation model (DEM) of the regions was created using ArcGIS software. The DEM file is incorporated into LS Rapid software to get the topographies. The present study assumed that the failure begins in the steeper portion of a slope, and the failure surface was created using an ellipsoidal sliding surface setting in the steepest part of the hill slope.

Soil Properties

The soil properties required for the simulation are including steady-state shear strength (τ_{ss}), lateral earth pressure ratio (k), peak friction angle (ϕ_p), peak cohesion (c), friction angle during motion (ϕ_m), shear displacement at the start of strength reduction, shear displacement at the beginning of steady-state, pore pressure generation rate, and unit weight of the soil (γ). In this study, the residual shear strength of the soil determined from the undrained triaxial shear test is considered to be steady-state shear strength. The properties of soils collected from the soil slopes of different locations are given in Table 23.2.

Table 23.2 Soil properties of slopes located at different sites (Geotechnical lab, NIT Calicut)

Location of soil sample	Unit weight (kN/m^3)	Shear strength parameters		Lateral earth pressure coefficient (k)	Shear strength of the soil (kPa)
		c (kPa)	ϕ(°)		
Aadit					
Top	17	4	35	0.426	74
Middle	17.2	4	32.2	0.467	66.5
Bottom	18.2	5	35.2	0.423	75
Kallar					
Top	13	5	24.8	0.58	51
Middle	13.4	5	27.1	0.54	56.1
Bottom	17	5	28	0.53	58.2
Mavadi					
Top	12.8	1	14.3	0.753	26.5
Middle	15.8	5	15.3	0.736	32.3
Bottom	14.6	5	25.8	0.56	53.3
Kakkattuppara					
Top	15.9	20	18.3	0.68	35
Middle	13.8	25	19.3	0.66	60
Bottom	15.9	15	17.8	0.7	47.3
Kavalappara					
Top	14.4	0	30	0.33	25
Middle	14.5	0	30	0.33	25
Bottom	14.3	0	30	0.33	25
Mananthavadi					
Top	13.5	12	34.7	0.43	81.24
Middle	13.7	12	33	0.45	76
Bottom	15.8	25	34.6	0.43	83
Puvaramthodu					
Top	13.5	10	32	0.47	72
Middle	14	10	33	0.45	74.9
Bottom	18	12	31	0.48	72

Numerical Simulation of Rainfall Induced Landslides

Average pore pressure ratios (PPRs) build in the soil slopes during rainfall are used to vary to study the effect of rainfall intensity on landslide stability. An increase in rainfall increases the saturation level of the soil that leads to building the pore pressures. In turn, it increases the average pore water pressure of the soil. At higher rainfall intensity, the soil slope becomes fully saturated with a PPR of 1, and it becomes unsaturated with PPR of 0.7, 0.5, and 0.1 at moderate to low rainfall intensities. The present study used to vary the pore pressure ratios from 0.1 to 0.9 to analyze the failure of the soil slopes under various rainfall intensities. Table 23.3 presents the detailing on the unstability of soil slopes at different locations, including the maximum vertical depth and the volume distribution of sliding mass and the rainfall intensity, i.e., PPR at which the landslide is initiated. From the simulation test results, the slopes located at Mavadi (Idukki) and Kakkattuppara (Wayanad) regions fail at a low pore pressure ratio of 0.1 with very low rainfall intensity. It also found that the soil slope located at Kakkattuppara has an enormous volume of landslide mass and can be considered critical.

It observed that the soil slopes located at Puvaramthondu, Kallar, and Mananthavadi areas are initiated to fails at low rainfall intensity with a PPR of 0.3–0.5 onward. However, the slopes at Kavalppara and Aadit are initiated to fail at high rainfall intensities with a PPR of 0.7 onward. The typical results on the simulation of progressive failure of soli slope located at Kakkattuppara subjected to a pore pressure ratio of 0.7 are shown in Fig. 23.2. Similar kinds of progressive failures are also produced in other cases of soil slopes. Figure 23.3 shows the sliding mass surface details in longitudinal section of soil slope located at Kakkattuppara subjected to a pore pressure ratio of 0.7. It finds that the green color boundary shows the original slope surface before failure; dense red color indicates the sliding surface, and the pink color boundary shows the surface of landslide mass after sliding failure. It shows the stable and unstable parts of the slope and the deposition region of the landslide mass.

Table 23.3 Failure details of the soil slopes tested in the present study

Location	Maximum vertical depth of the landslide body (m)	Volume of landslide body (m^3)	Pore pressure ratio to initiate slope failure
Aadit, Idukki	19.1	123.1×10^3	0.7
Kallar, Idukki	37.51	448.6×10^3	0.4
Mavadi, Idukki	53.78	513.3×10^3	0.1
Kakatttupara, Wayanad	68.05	1178×10^3	0.1
Kavalappara, Wayanad	24.91	341.3×10^3	0.7
Mananthavadi, Wayanad	34.1	327.5×10^3	0.5
Puvaramthondu, Wayanad	48.65	949.3×10^3	0.3

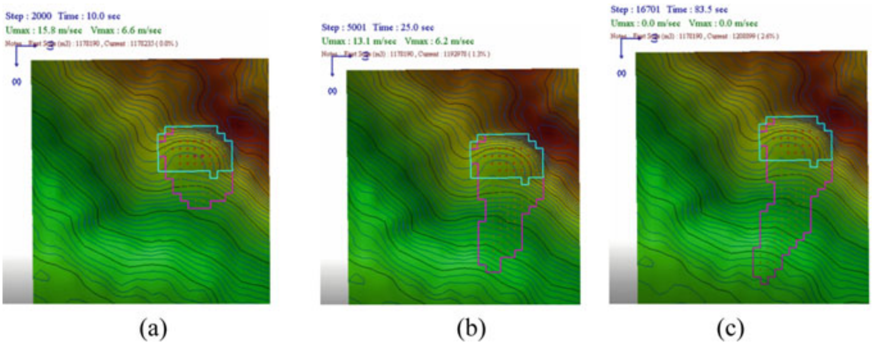

Fig. 23.2 Progressive failure of soil slope located at Kakkattuppara subjected to high rainfall intensity with PPR of 0.7: Land slide at **a** initiation; **b** distribution; and **c** deposition stages

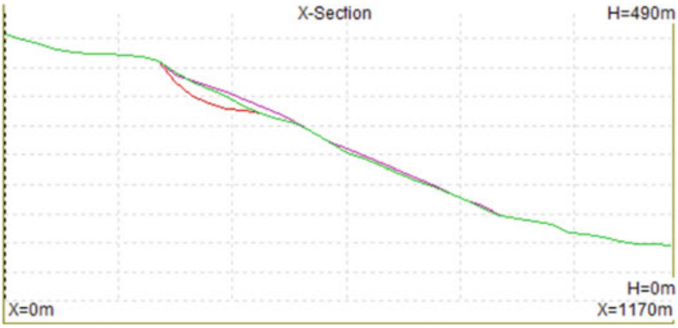

Fig. 23.3 Sliding surface in longitudinal section of soil slope situated at Kakkattuppara region subjected rainfall intensity with PPR of 0.7

Numerical Simulation of Seismically Induced Landslides

The slopes were subjected to low seismic amplitude of 0.009 g to study the influence of minor dynamic loading on the failure of soil slopes. The details of the seismic time history used to perform the simulations are given in Table 23.4. Numerical simulations were performed on the dynamic stability of landslides at no rainfall intensity, i.e., PPR = 0 and moderate rainfall intensity with PPR of 0.5 conditions. Table 23.5 summarizes the influence of seismic load alone and combined seismic load with moderate rainfall intensity on the susceptibility of soil slopes failure. From the simulation results, it has been found that the soil slopes located at Aadit (Idukki) and Puvaramthodu (Wayanad) were safe under seismic load alone at no rainfall intensity. However, it caused local deformation in soil slopes located at Kallar (Idukki), Mavadi (Idukki), and Kavalappara (Wayanad) regions. It is also seen that the soil slopes located at Kakkattuppara and Mananthavadi (Wayanad) areas are failed under seismic load alone at no rainfall intensity. All the soil slopes situated at different places are

Table 23.4 Details of the seismic time history used for the simulations

Location	Phek-Nagaland
Latitude	25.7 N
Longitude	94.6 E
Origin time	01–07–2012 04:13
PGA	0.009 g
Record duration	65.000 s

Table 23.5 Failure conditions of soil slopes subjected to seismic load and rainfall intensity

Location	Seismic load alone (PPR = 0)	Seismic load with moderate rainfall intensity (PPR = 0.5)
Aadit, Idukki	No failure	Failed
Kallar, Idukki	Local deformation	Failed
Mavadi, Idukki	Local deformation	Failed
Kakatttupara, Wayanad	Failed	Failed
Kavalappara, Wayanad	Local deformation	Failed
Mananthavadi, Wayanad	Failed	Failed
Puvaramthondu, Wayanad	No failure	Failed

failed under the influence of combined action of seismic load with moderate rainfall intensity, i.e., PPR of 0.5.

Parametric Study

The present study is extended to study the effect of rainfall intensity, dynamic loading amplitude, and soil properties on landslide stability of soil slopes located at different places. The simulation results provide the maximum velocities of soil flow and volume of sliding soil mass in the lateral and vertical directions of soil slopes.

Effect of Rainfall Intensity, i.e., Average Pore Pressure Ratio

Initially, the study focuses on the effect of rainfall intensity on the maximum velocity of soil slope deformation at the failure stage. Table 23.6 summarizes the variation of maximum flow velocities of the soil slopes in a lateral direction with different pore pressure ratios representing the rainfall intensity. Results indicate that the maximum flow velocities of soil slope deformations increase with increased rainfall intensities with pore pressure ratios in the range of 0.1–0.9. Similar results are also produced in the vertical direction but less significant when compared in the lateral movement. It suggests that the effect of rainfall intensity is more significant on soil flow velocities at failure state. The increase of soil flow velocity with rainfall intensity is due to a reduction in the effective strength of soil with built-up of pore pressure. The present study also focuses on the effect of rainfall intensity on the variation of volumetric landslide soil mass distribution at the failure stage. The slopes become unstable with large volumetric soil displacements as the rainfall intensity increases, i.e., pore pressure ratios. Results indicate that the soil slopes at Mavadi (Idukki) and Kakkattuppara (Wayanad) are inconsistent, and others are stable at low rainfall intensity with a PPR of 0.1. It may be due to the high slope angle and low shear strength for Mavadi and Kakkattuppara soil slopes. The volumetric landslide soil mass distribution is increased with an increase in rainfall intensities. Table 23.7 shows the variation of volumetric landslide soil deformations of the soil slopes with different pore pressure ratios representing the rainfall intensity.

Table 23.6 Summary on variation of maximum flow velocities of the soil slopes in lateral direction with rainfall intensity, i.e., different pore pressure ratios

Location of soil slope	Maximum velocities of soil mass movement in lateral direction (u_{max}), m/s, with rainfall intensity, i.e., PPR of			
	0.1	0.5	0.7	0.9
Aadit, Idukki	0	0	18.5	19.8
Kallar, Idukki	0	20	20.5	31.7
Mavadi, Idukki	14	14.7	26.8	28.9
Kakattupara, Wayanad	10	15.3	17.4	52.5
Kavalappara, Wayanad	0	0	52.2	73
Mananthavadi, Wayanad	0	21	26.6	30.9
Puvaramthondu, Wayanad	0	25.2	26.2	38.3

Table 23.7 Summary on variation of volumetric landslide soil deformations of the soil slopes with rainfall intensity, i.e., different pore pressure ratios

Location of soil slope	Volumetric landslide soil deformations of the soil slopes, $\times 10^3$ m^3, with rainfall intensity, i.e., PPR of		
	0.5	0.7	0.9
Aadit, Idukki	129	135	136
Kallar, Idukki	484	489	493
Mavadi, Idukki	565	565	565
Kakattupara, Wayanad	1179	1209	1246
Kavalappara, Wayanad	0	366	376
Mananthavadi, Wayanad	125	141	142
Puvaramthondu, Wayanad	945	945	945

Table 23.8 Effect of seismic loading on volumetric flow of soil mass of landslides

Location of soil slope	Volumetric flow of soil mass, × 10^3 m^3		
	Seismic load alone with no rainfall (PPR = 0)	Rainfall intensity alone (PPR = 0.5)	Seismic load + moderate rainfall intensity (PPR = 0.5)
Aadit, Idukki	Stable	Stable	135.5
Kallar, Idukki	Local deformation	484.6	486.0
Mavadi, Idukki	545.2	564.6	570.7
Kakatttupara, Wayanad	1237.5	1179.4	1295.6
Kavalappara, Wayanad	Local deformation	Stable	375.5
Mananthavadi, Wayanad	256.2	124.6	270.4
Puvaramthondu, Wayanad	Stable	945.2	980.9

Effect of Dynamic Loading

The effect of seismic loading with low amplitude is studied on the stability of landslides in dry conditions and partially saturated with moderate rainfall intensity, i.e., PPR of 0.5. Table 23.8 summarizes the effect of seismic loading combined with moderate rainfall intensity on landslide volumetric flow of soil mass. It is found that the seismic load, along with moderate rainfall intensity, causes a significant effect on landslide occurrence with high maximum flow velocities of soil movements and also the volume of sliding of soil mass.

Effect of Cohesion

The cohesion strength of soil located at the Kakkattupara soil slope has been varied to study the effect of cohesion on landslide mass. The cohesive strength of the soil slope was varied as 30, 40, and 50 kPa to study the effect of cohesive strength on landslide. The triggering factor considered was seismic load with moderate rainfall intensity. The maximum soil flow velocities in lateral and vertical directions and the percentage variation in volumetric soil flow of landslide under different cohesion values are shown in Fig. 23.4. It can be noted that when the cohesion of the soil increased from 30 to 50 kPa, the maximum velocities of sliding mass in the horizontal direction decreased from 15.5 to 6.8 m/s. Similarly, the flow velocities in the vertical direction decreased from 10.2 to 4.8 m/s. Also, the percentage variation in the volume of sliding soil mass decreased from 5.6 to 2.1%. Hence, it is proved that soil cohesion strength greatly helps mitigate the occurrence of landslides.

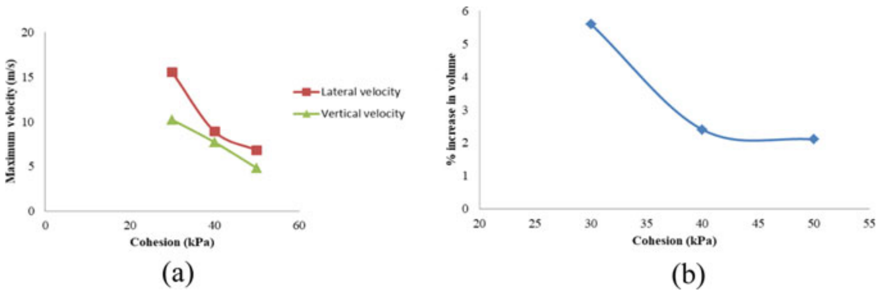

Fig. 23.4 Variation of **a** maximum velocity of soil flow, and **b** volume of sliding soil mass with cohesion strength of soil on Kakkattupara soil slope under seismic load with moderate rainfall intensity

Table 23.9 Effect steady-state shear strength on volume of sliding soil mass during landslide

Location of soil slope	Slope (°)	Steady-state shear strength (kPa)	% Variation in volume of sliding soil mass (%)
Mavadi, Idukki	44.6	37.3	15.4
Kakkattuppara, Wayanad	45	47.4	10
Kallar, Idukki	44.2	55.1	6.6

Effect of Steady-State Shear Strength of Soil

The present study uses the steady-state shear strengths of three soil slopes located at Mavadi, Kakkattuppara, and Kallar sites to study the influence of steady-state shear strength on the volume of sliding soil mass. These soil slopes are having a similar slope angle of about 44–45°. The effect of steady shear strength is examined on the volume of sliding soil mass of landslides that occurred due to 90% rainfall intensity. Table 23.9 shows that the sliding area covered by a landslide decreases with an increase of steady-state shear strength of the soil. As the steady-state shear strength of the soil increases from 37.3 to 55.1 kPa, the percentage variation in the volume of sliding soil mass decreases from 15.4 to 6.6%. Thus, the steady-state shear strength of soil mass affects the area covered by the landslide mass.

Conclusions

The present study has performed numerical simulations of landslides that occurred in seven soil slopes of Idukki and Wayanad districts in Kerala state. The major conclusions drawn from the current study are given below.

- Soil slopes located at Mavadi and Kakattupara are initiated to fails at even very low rainfall intensity with a PPR of 0.1 onward. It also found that the soil slopes located at Puvaramthondu, Kallar, and Mananthavadi are initiated to fails at low rainfall intensity with a PPR of 0.3–0.5 onward. However, the slopes at Kavalppara and Adit are initiated to fail at high rainfall intensities with a PPR of 0.7 onward. It indicates that soil slopes located at Mavadi and Kakattupara causing severe landslide mass distribution compared with other soil slopes.

- All the soil slopes tested except two hill slopes located at Aadit and Puvaramthodu areas are failed under dynamic loading alone with no rainfall condition. Soil slopes that are stable under moderate rainfall intensity failed when they were subjected to a combination of dynamic loading with moderate rainfall intensity. Thus, dynamic loading can increase the instability of landslides occurred at average rainfall intensities.
- An increase in cohesion strength of the soil causes a decrease in the maximum velocities of soil flow and volume of soil mass distribution. Improving the steady-state shear strength of the soil can reduce the occurrence of landslides.

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