Physics-Based Hydro-Geotechnical Modelling for Regional Assessment and Mitigation of Rainfall-Induced Landslide Hazards through IoT-Enabled Real-Time Field Monitoring and Early Warning

Research Scholar: Musaib Ahmad **Supervisor: Dr. Divya PV**

Abstract

Rainfall-induced landslides are a major natural hazard in the Western Ghats of Kerala, India, resulting in substantial loss of life, damage to infrastructure, and socioeconomic disruption. Their occurrence is governed by complex interactions among rainfall infiltration, surface and subsurface hydrological processes, topography, and geotechnical properties. Effective mitigation of these hazards requires an integrated framework combining regional identification of landslide-susceptible and hazardous areas, rainfall threshold assessment, and real-time monitoring and early warning. This research aims to develop an integrated framework for the regional assessment and mitigation of rainfall-induced landslide hazards in the Idukki district of Kerala, India, through advanced hydro-geotechnical modelling, geospatial analysis, and IoT-enabled real-time field monitoring and early warning systems.The research begins with a comprehensive characterization of the study area through field investigations, borehole investigations, soil sampling, groundwater monitoring, laboratory testing, and infiltration and soil suction measurements. High-resolution digital elevation models (DEMs) derived from drone-based LiDAR surveys, along with spatially distributed geotechnical soil properties, are incorporated into the regional hydro-geotechnical modelling framework. The three-dimensional transient hydrological model GEOtop is coupled with a slope stability model to simulate the spatiotemporal evolution of soil moisture, pore-water pressure, and factor of safety under varying rainfall conditions. This integrated modelling approach provides the physical basis for regional landslide susceptibility and hazard assessment.

The research further develops physics-based Landslide Susceptibility Mapping (LSM) and Landslide Hazard Assessment (LHA) frameworks. Most conventional landslide susceptibility mapping approaches rely on heuristic, statistical, or machine learning methods that establish relationships between historical landslide occurrences and terrain-conditioning factors. However, many of these approaches do not explicitly account for the geotechnical properties of soil, particularly its unsaturated hydraulic and mechanical characteristics, or the underlying physical mechanisms governing rainfall-induced slope failure. To address these limitations, a physics-based susceptibility assessment framework is developed by incorporating spatially distributed geotechnical properties, including unsaturated soil characteristics, into advanced hydro-geotechnical modelling. By explicitly representing the hydrological processes and geotechnical failure mechanisms, the proposed framework provides a more physically realistic assessment of regional landslide susceptibility in the study area. Its predictive capability and applicability are evaluated through validation against historical landslide occurrences. Furthermore, numerical simulations are conducted under varying rainfall intensities, durations, and antecedent hydrological conditions to investigate their influence on slope instability. Based on these simulations, regional rainfall thresholds are developed to characterize conditions conducive to slope failure and support rainfall-based landslide early warning.

The developed hydro-geotechnical susceptibility model is further utilized to identify critical slope locations for detailed field monitoring. Accordingly, one of the identified critical slopes is selected for an instrumented real-time monitoring programme using IoT-enabled monitoring system. Continuous monitoring of atmospheric conditions, subsurface hydrological responses, and slope deformation provides insights into the evolution of soil moisture, suction, pore-water pressure, and slope response to rainfall infiltration, thereby facilitating a better understanding of rainfall-induced slope failure mechanisms. The field observations also provide a basis for evaluating the hydro-geotechnical modelling framework and developing an XGBoost-based machine learning model for predicting slope instability. By integrating the trained model with real-time IoT observations and rainfall information, the framework enables continuous assessment of slope conditions, prediction of potential instability, and timely early warning. Furthermore, the monitoring information supports the identification of critical slope conditions and the planning of site-specific mitigation measures. The proposed framework is expected to improve landslide prediction and support evidence-based early warning, disaster preparedness, and mitigation strategies in landslide-prone regions of the Western Ghats.

Keywords: Rainfall-induced landslides, Slope stability, Hydro-geotechnical modelling, Landslide susceptibility, Regional rainfall thresholds, IoT-Enabled Real-Time Field Monitoring, Machine learning, Early warning system, GEOtop.