

Consequences of Slope Stability Issues and Mitigating Strategies in Hydropower Projects of Nepal from the Perspectives of Rasuwa Flashflood

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Abstract: Nepal's rapidly expanding hydropower sector is predominantly located within the steep, tectonically active, and geologically complex Himalayan terrain, where slope instability threatens construction safety, infrastructure integrity, project schedules, and long-term operational performance. Slope failures commonly result from adverse geological structures, unfavorable discontinuity orientations, steep excavations, weathering, groundwater ingress, surface-water erosion, and inadequate geological and geotechnical investigations. These factors can cause rock failures, debris movements, rockfalls, and other forms of slope instability. The catastrophic Rasuwa flash flood of August 2026 provides an example of the interaction among extreme hydrometeorological events, mass movements, river-channel processes, and infrastructure vulnerability. The event highlights the need for an integrated, multi-hazard, and risk-informed approach to hydropower planning and design beyond conventional site-specific slope-stability assessments. Lessons from Rasuwa underscore the importance of comprehensive geological and geotechnical investigations, mechanism-specific slope-stability analyses, effective excavation and stabilization designs, systematic drainage and erosion-control measures, continuous monitoring, early-warning systems, and resilient access and emergency-response arrangements. Integrating these measures into hydropower development is essential to reducing disaster risks, protecting critical infrastructure, minimizing project disruptions, and strengthening the long-term safety and resilience of hydropower projects in Nepal's fragile Himalayan environment.

Keywords: *Slope stability, Rasuwa flash flood, Mass movement, Multi-hazard risk, Slope stabilization, Early warning systems, Infrastructure resilience.*

Introduction

Hydropower development has become an important part of Nepal's infrastructure and economic growth, with numerous projects being constructed across the Himalayan region. However, the steep topography, active tectonic conditions, complex geological formations, and highly fractured rock masses create significant challenges for the construction and long-term operation of hydropower infrastructure. Among these challenges, slope instability remains a major concern, as it can affect construction safety, damage

infrastructure, delay project completion, and increase maintenance costs. The interaction between natural geological conditions and human activities, particularly excavation and slope modification, further increases the possibility of slope failures in mountainous terrain.

Slope instability in hydropower projects is influenced by several geological, geotechnical, and environmental factors. Unfavorable discontinuity orientations, persistent joints, weathered rock masses, steep excavation geometries, groundwater infiltration, and surface-water erosion can significantly reduce slope stability. These conditions may lead to rockfalls, landslides, debris movements, and structurally controlled rock failures. Furthermore, inadequate geological investigations and insufficient understanding of site-specific conditions can increase the vulnerability of hydropower structures and surrounding infrastructure. Therefore, proper geological assessment, slope-stability analysis, and appropriate stabilization measures are essential during project planning, construction, and operation.

The catastrophic Rasuwa flash flood of August 2026 highlights the interconnected nature of natural hazards and infrastructure vulnerability in the Himalayan region. The event severely affected the Bhote Koshi-Trishuli corridor, causing extensive damage to infrastructure and demonstrating how slope movements, flood processes, and river-channel changes can contribute to cascading hazards. It emphasizes that slope instability cannot always be assessed as an isolated geological problem, particularly in areas exposed to multiple natural hazards.

In this context, understanding the causes and consequences of slope instability is essential for improving the safety and resilience of hydropower development in Nepal. An integrated approach combining geological and geotechnical investigations, slope stabilization, drainage management, continuous monitoring, early-warning systems, and emergency preparedness can help reduce risks associated with slope failures and extreme flood events. The lessons from the Rasuwa disaster provide important insights into the need for multi-hazard assessment and risk-

informed engineering practices in Himalayan hydropower projects.

Consequences of slope instability and mitigation strategies in hydropower projects

Slope instability poses significant challenges to hydropower development in Nepal, particularly in the Himalayan region, where steep terrain, complex geological structures, and active tectonic conditions increase the risk of slope failures. These failures can result in damage to hydropower infrastructure, disruption of construction activities, delays in project completion, and increased maintenance costs. Geological factors such as unfavorable discontinuity orientations, persistent joints, weathered rock masses, and groundwater infiltration contribute to slope instability. Furthermore, excavation activities and inadequate assessment of site-specific geological conditions can increase the vulnerability of slopes, leading to rockfalls, landslides, debris movements, and other forms of mass movement.

The August 2026 Rasuwa flash flood provides an important example of the consequences of interconnected geological and hydrological hazards. The event severely affected the Bhoté Koshi–Trishuli corridor and surrounding hydropower infrastructure, highlighting how extreme flood processes, slope movements, and changes in river-channel conditions can collectively threaten infrastructure stability. Such cascading hazards can damage hydropower structures, interrupt access routes, and create additional risks during construction and operation. The disaster emphasizes the importance of considering multiple interacting hazards rather than evaluating slope stability as an isolated engineering problem.

To reduce these risks, comprehensive geological and geotechnical investigations are essential during hydropower project planning and development. Detailed assessments of rock-mass conditions, discontinuity characteristics, groundwater movement, and potential failure mechanisms can help identify unstable slopes and determine suitable stabilization measures. Appropriate excavation design, slope reinforcement, drainage systems, and erosion-control measures are important for maintaining slope stability. Continuous monitoring and early-warning systems can also support the early identification of potentially hazardous conditions, allowing timely preventive actions. In addition, resilient access networks and effective emergency-response arrangements are necessary to minimize disruptions during extreme events.

The lessons from the Rasuwa flash flood highlight the need for an integrated, multi-hazard and risk-informed approach to hydropower development in Nepal. Combining geological investigations, engineering

design, slope stabilization, monitoring, and disaster preparedness can improve infrastructure resilience and reduce the consequences of future slope failures. These strategies are particularly important for ensuring the safety, reliability, and long-term sustainability of hydropower projects in the geologically complex Himalayan environment.

Conclusion

Slope instability remains one of the major geological and geotechnical challenges affecting hydropower development in Nepal's Himalayan region. The combination of steep slopes, complex geological structures, fractured and weathered rock masses, groundwater movement, and excavation activities creates conditions that can lead to different forms of slope failure. These failures threaten construction safety, infrastructure stability, project schedules, and long-term hydropower operations. Therefore, understanding site-specific geological conditions and identifying potential failure mechanisms are essential for effective slope management.

The August 2026 Rasuwa flash flood further demonstrates how interconnected natural hazards can increase the vulnerability of hydropower infrastructure. The interaction of slope movements, flood processes, sediment transport, and river-channel changes highlights the limitations of assessing slope stability independently from surrounding environmental hazards. This event emphasizes the importance of adopting an integrated, multi-hazard approach rather than relying solely on conventional site-specific stability assessments.

Overall, improving the resilience of hydropower projects requires comprehensive geological and geotechnical investigations, appropriate excavation and stabilization designs, effective drainage and erosion-control measures, continuous monitoring, and reliable early-warning systems. Strengthening access infrastructure and emergency-response arrangements is equally important for reducing the consequences of future disasters. By incorporating these measures into hydropower planning, construction, and operation, Nepal can improve infrastructure safety, minimize disaster-related losses, and support more sustainable hydropower development in the Himalayan region.