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Influence of Soil Saturation and Seismic Load on Slope Behavior in Post-Landslide Jure Slope, Nepal

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Abstract

Landslides in Nepal pose a significant threat due to the country's active tectonics, delicate geology, rugged topography, and uncertain climate. The Jure landslide that occurred on August 2, 2014, has garnered particular attention due to the unprecedented loss of life and properties. This paper investigates the influence of soil saturation and seismic load on slope behavior in the post-landslide jure slope, Nepal utilizing RocScience phase-2, finite element analysis software. The study is performed by geomechanical stimulation of the slope model using shear strength reduction method, appropriate boundary conditions and Mohr column and Hoek-Brown failure criteria. The results show that higher saturation levels lead to reduced shear strength and increased displacement, while positive horizontal seismic loads decrease the critical strength reduction factor, increasing susceptibility of the slope to failure. Remedial measures developed accordingly can protect the affected region from future landslides during heavy rainfall and earthquakes. By enhancing our understanding of slope behavior, this study helps to improve disaster preparedness and resilience in similar regions facing natural hazards.

Keywords: Soil saturation • Seismic load • Seismic coefficients • Slope stability • Shear Strength Reduction (SSR) • Strength Reduction Factor (SRF) • Critical SRF • Displacement • Debris flow • Phase-2 • RocScience

Introduction

Nepal's susceptibility to disasters, stemming from its active tectonics, delicate geology, rugged topography, and uncertain climate results in significant loss of life and property each year and affects the nation's overall economic progress. Nepal experiences a higher intensity of natural hazards, such as landslides, compared to other countries in the world, considering its territorial area and population [1]. These hazards, particularly landslides, are particularly prominent during the monsoon season and major earthquake events.

On August 2014, a major landslide called Jure landslide struck in a densely populated area 80 km Northeast of Nepal's capital Kathmandu in Jure, Sindhupalchok District. The landslide was about 1.3 km in length and 0.8 km wide at the bottom. It was one of the deadliest landslides in Nepal's history, resulting in a death toll of more than 156 people. Along with destroying houses, land and properties, it deposited a large volume of debris material at the existing waterway of the Sunkoshi River. The Araniko Highway running through that area was severely damaged. Six decades ago, a part of the same hill had toppled down rendering serious human casualties, and that area was declared a slide-prone area by many researchers and field workers.

Currently, a post-landslide slope can be observed in the area with a debris layer over the phyllite rock mass (Figure 1). It is still susceptible to the effect of rainfall and seismic forces which if determined, can be used to understand the slope stability and develop remedial measures [2].

Figure 1. Jure landslide region.

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Static seismic loading is the application of lateral forces on a slope due to seismic activity. These forces are caused by the ground shaking during an earthquake and can induce additional stress and displacement in the slope material [3]. Similarly, saturation significantly affects slope stability, particularly in landslide-prone areas like jure slope in Nepal [4]. When soil reaches its saturation point, its physical properties are changed, such as decrease in shear strength and increase in pore water pressure. These changes can lead to reduced slope stability, triggering landslides. Understanding the combined effect of soil saturation and seismic loading on slope behavior is vital for assessing the vulnerability of slopes and developing effective mitigation measures (Figure 2).

Figure 2. Study area.

In this study, we use the concept of Shear Strength Reduction (SSR) as a measure to calculate slope stability and displacement. The basic concept of the SSR method is that: The strength parameters of a slope are reduced by a certain factor called Strength Reduction Factor (SRF), and the finite element stress analysis is computed [5]. This process is reiterated for different values of SRF until the model becomes unstable i.e., the analysis results do not converge. This determines the critical SRF, which is equivalent to the "safety factor" of the slope [6]. The maximum value of SRF at which the model remains stable gives the value of the Critical SRF. Similarly, the maximum displacement is the maximum value of total displacement which occurs at any point in the model.

Materials and Methods

The study involves finite element analysis of the post-landslide slope surface using roc science phase-2 software to determine critical SRF, displacement corresponding to critical SRF, and maximum displacement.

The portion of jure landslide in consideration lies roughly at coordinates 27°46’N, 85°52’E. It is located in jure village of Ramche village development committee, Sindhupalchowk District.

Data obtained from the ERT survey done by road division office, Chautara was first used to develop a lithological section profile of the landslide area, which could be differentiated into Slid mass (Debris layer) and Bedrock layer. The debris layer was divided into five further layers, as shown in the Figure 3.

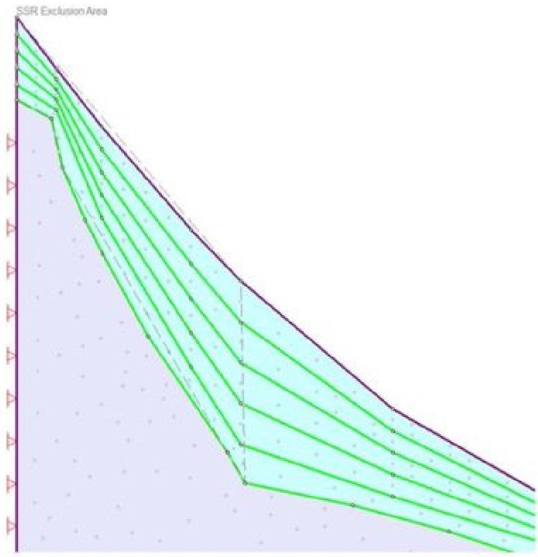

Figure 3. A portion of model showing different layers of debris and rock in phase-2 software.

Here, the dry stage (without rainfall) is taken as stage-1. Then in the monsoon season, rainwater seeps down, causing the top layer to lower layers to get saturated gradually, which are modeled as stage 2 to stage 6 (full saturation condition), as shown in the Table 1 below.

Stage	Saturation level in debris layers
1	No saturation in any layer
2	Full saturation in the 1st (top) layer
3	Full saturation in the 1st and 2nd layers
4	Full saturation in the 1st, 2nd, , 3rd layers
5	Full saturation in the top four layers
6	Full saturation in all layers

Table 1. Modeled as stage 2 to stage 6 (full saturation condition).

The section profile was then modeled in roc science phase-2 software, where material properties of each soil layer determined from laboratory tests (Figure 4) were assigned along with boundary conditions. SSR exclusion area was fixed in the profile to remove anomalous results. Analysis wasperformed for zero saturation, partial saturation in each layer, and full saturation (Table 2).

Figure 4. Phyllite and debris layers in the landslide zone.

Material	Dry soil	Saturated soil	Rock (Schist interbedded with phyllite)
Failure criteria	Mohr-Coulomb	Mohr-Coulomb	Generalized Hoek and Brown
Unit weight	18 kN/m^3	21.7 kN/m^3	29 kN/m^3
Elastic properties	Modulus of elasticity=105 kPa	Modulus of elasticity=105 kPa	Modulus of elasticity of intact rock=54000 MPaModulus of elasticity of rock mass=29306428 KPa
Shear parameters	Poisson ratio: 0.3 Cohesion (peak)=5 kPa Angle of friction (peak)=32°	Poisson ratio: 0.3 Cohesion (peak)=6.75 kPa Angle of friction (peak)=28.55°	Poisson ratio: 0.3 Intact rock uniaxial compressive Intact rock uniaxial compressive strength=80 Mpa GSI=60 mi: 7 Disturbance factor D=0

Table 2. Material properties for different soil and rock layers.

Static seismic load of horizontal coefficient 0.1 for severe earthquakes and vertical coefficient 0.025 (taken as an average value that generally ranges from 0 to 0.05), was applied with varying directions for all stages of saturation. The output data of the analysis (SRF, corresponding displacement, max displacement) was noted to further analyze and determine the effect of saturation and seismic loadings, and various corresponding trends were observed (Figure 5).

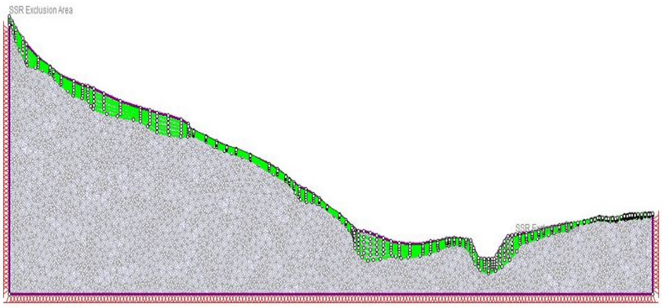

Figure 5. 2D-model of longitudinal section in phase-2 software.

Results

The model was computed in roc science phase 2, and the total displacement for different values of SRF was obtained (Figures 6 and 7). Also, the maximum total displacement and critical SRF values were noted. Then, various trends were obtained for varying saturation levels and seismic intensity, as shown in the Figures 8-10.

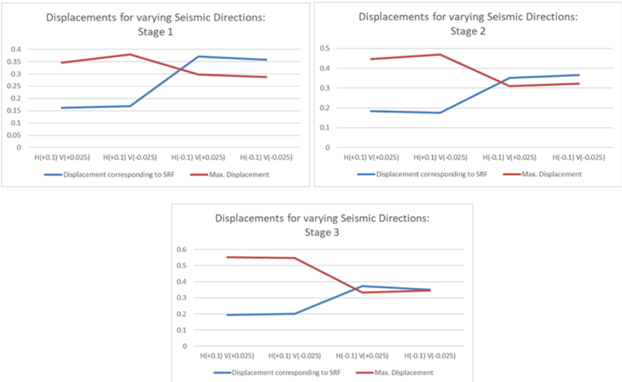

Figure 6. Displacement for varying seismic directions stages 1-3.

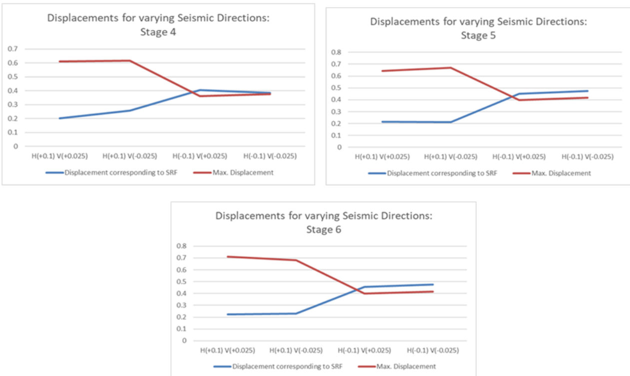

Figure 7. Displacement for varying seismic directions stages 4-6.

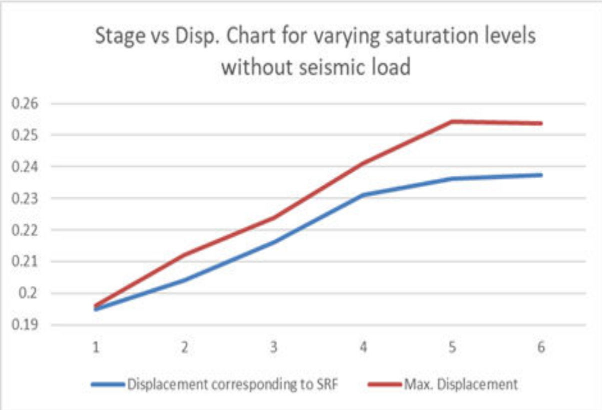

Figure 8. The above mentioned graphs shows displacement corresponding to SRF and Max. displacement.

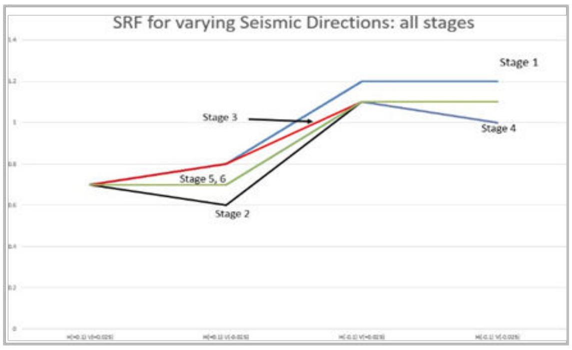

Figure 9. SRF for varying seismic directions: All stages.

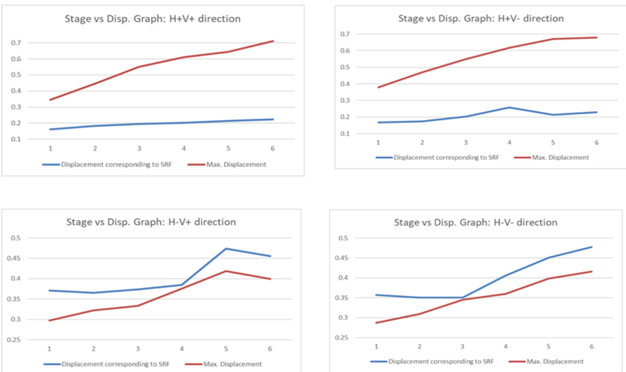

Figure 10. Stages *vs.* displacements.

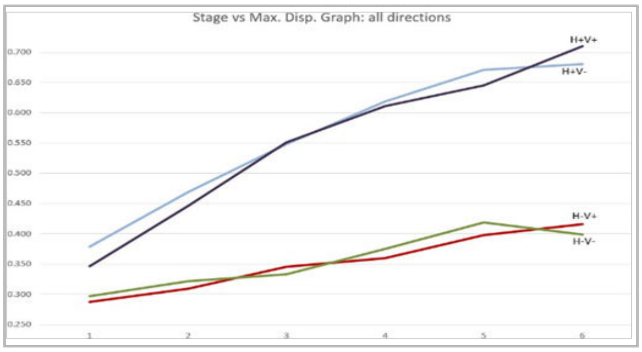

Figure 11. Stages *vs.* displacements for all directions.

From the figures, the following observations were made:

- The maximum value of critical SRF (outside SSR exclusion area) was observed as 1.2 for stage 1 with negative static seismic load in the horizontal direction.
- The least values of critical SRF (outside SSR exclusion area) were observed as 0.7 in stages 1 to 5 with positive static seismic load in the horizontal direction.
- Without saturation and seismic load, the critical SRF was found to be 1. However, with the increase in saturation, the SRF decreased to 0.9 in all stages.

Discussion

- When seismic load is not applied, the corresponding displacement increases with the increase in saturation. At stage 1 (dry condition), displacement corresponding to critical SRF and stage displacement are roughly the same. However, a substantial difference can be observed between the displacement values when it approaches stage 6 (fully saturated condition)
- When the seismic forces are applied, negative horizontal seismic loads do not pose the threat of slope failure. Whereas, in the case of positive horizontal seismic load, the value of critical SRF decreases. That is: Negative horizontal forces are less dangerous compared to positive ones.
- The difference between displacement corresponding to critical SRF and stage displacement for all stages is wider in the case of horizontal seismic coefficient. Whereas, the difference is lesser in the case of negative horizontal seismic coefficients.
- For all stages, with the increase in saturation, the maximum displacement line graph for positive horizontal seismic coefficients is steeper than negative ones, meaning that seismic loads in the horizontal direction are more sensitive.

Conclusion

This research paper investigates the impact of soil saturation and seismic load on the slope behavior in the post-landslide Jure slope in Nepal. Utilizing finite element analysis and the Shear Strength Reduction (SSR) method, the study assessed slope stability and displacement under varying saturation and seismic loading conditions. Higher saturation reduced shear strength and increased displacement, while positive horizontal seismic loads decreased slope stability. To protect this slope region from further landslides during heavy rainfall and earthquakes in the future, it is important to develop remedial measures such as implementing effective drainage systems, soil stabilization using geosynthetics and vegetation which focus on effective drainage and minimizing the effects of horizontal seismic loads. Also, in future debris flow, developing flow channels can divert debris away from settlements and infrastructures, spreading awareness to local people, and developing early warning systems can help protect valuable lives and properties.

It is important to note that this study focused on the specific case of the Jure slope, and its findings may not directly apply to areas with different geological and climatic conditions. Therefore, future research should be done to explore additional factors influencing slope behavior, consider diverse case studies and integrate real-time data with the aim of enhancing the accuracy and reliability of slope stability assessments. By understanding slope behavior under various conditions better, we can improve disaster preparedness and enhance the resilience of communities facing natural hazards in Nepal and similar regions worldwide.

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