

Risk assessment and stability analysis of a recent landslide at Vishnuprayag on the Rishikesh–Badrinath highway, Uttarakhand, India

S. Sarkar*, Koushik Pandit, Mahesh Sharma and Ashish Pippal

CSIR-Central Building Research Institute, Roorkee 247 667, India

A massive landslide was triggered on 19 May 2017 at Vishnuprayag near Joshimath, Uttarakhand, India. The landslide blocked the Rishikesh–Badrinath highway and halted traffic for about 24 h till the debris was removed and the road reopened. The Hathi Pahar hill in Vishnuprayag has been a landslide-prone zone because of the presence of loose boulders and large rock blocks on very steep slopes. The site was visited immediately after the landslide and a rapid field assessment of slope stability was carried out. The stability analysis was performed with limited geological and geotechnical data collected from field and laboratory. Based on the two-dimensional finite element analysis, it was inferred that the slope is marginally stable under static load, but fails under seismic loading. The slope could fail in future due to triggering factors such as heavy rainfall, earthquake and anthropogenic activities. This communication presents field observations and the subsequent stability analysis along with possible suggestive control measures.

Keywords: Control measures, landslides, risk assessment, slope stability.

LANDSLIDE occurrences are common in the Himalayan region largely because of its complex geology, tectonic instability, continuous erosion by rivers and streams, and high-intensity rainfall substantiated by upcoming hill-development activities. In the recent past, there have been landslide-associated disasters; one such major disaster occurred in 2013, when the Alaknanda and Bhagirathi valleys in NW Himalaya witnessed loss of lives and property due to landslides and debris flow. The region to the north of the Main Central Thrust (MCT) is characterized by many landslides and mass movements due to structurally disturbed rocks having complex folding, overthrusting as well as frequent occurrence of earthquake activities¹. In the upper reaches of the Alaknanda valley, many active landslides have caused threat to human life, infrastructure and property². The road sector particularly from Chamoli to Badrinath is a high landslide-prone zone due to the weak geological formation, steep slopes, highly dissected topography, seismically active area and high rainfall^{3,4}.

A massive landslide occurred on 19 May 2017 on the Rishikesh–Badrinath highway (NH-58) at Vishnuprayag about 8 km from Joshimath town, Uttarakhand, India. The landslide was located at 30°33′49.90″N and 79°34′01.85″E and falls in the Survey of India toposheet No. 53N/10. It was reported that nearly 15,000 tourists were stranded on either side of the landslide for more than 24 h, as the road of nearly 150 m length was completely damaged. The landslide occurred about 500 m away from Vishnuprayag, a confluence of the rivers Dhauliganga and Alaknanda (Figure 1). Huge chunks of rocks rolled down from the Hathi Pahar hill. The site was surveyed and landslide features such as geology, primary escarpment, rock joints, debris material, cracks, etc. were observed. The inferences drawn along with stability analysis and probable measures are presented here. Figure 2 shows a panoramic view of the landslide.

The landslide was surveyed on 24 May 2017 for risk assessment and possible suggestive measures. Geologically, the rocks in the area are gneiss belonging to the Central Crystalline Formation. A few rock samples were brought to the laboratory and tested in a point load testing machine to determine the strength. The point load testing of the intact rock in the laboratory and Schmidt's hammer test of the rock mass carried out in the field gave a compressive strength of 95 and 80 MPa respectively. There are two major geological discontinuity planes; one is the bedding plane dipping inside the hill and another is a steeply dipping joint plane in the outward direction from the slope. The area lies close to north of the MCT which is a major tectonic and seismically active zone.

The hill slope is very steep with an average slope angle of 70° (Figure 2). The main escarpment along the failure plane, i.e. the outward-dipping joint plane was developed at a height of about 70 m above the road level. The toe of the slide at the river level below the road has a thick pile of boulders and debris. The landslide debris deposited on the road comprised of huge boulders and rock fragments (Figure 3). The maximum size of such boulders was about 2 m × 1 m × 1.5 m.

The Hathi Pahar hill is a landslide-prone zone as it contains two more landslide potential sites close to the present one. Two years ago, a similar landslide event occurred at the same spot on 29 April 2015. In fact, the present landslide could be considered as reactivation of the previous landslide, which had already weakened the rock mass and exposed the rock joints facilitating the sliding of the overhanging rock blocks. This time a huge rock block got detached from the hill and broke while rolling downhill. The resulting boulders and fragmented rocks blocked the road, and a few fell into the river. It was inferred from field studies that the slide has occurred as planar failure on the already existing discontinuity plane dipping parallel to the slope. Figure 4 is a stereo plot showing the unfavourable geological discontinuity causing planar failure.

*For correspondence. (e-mail: ssarkar@cabri.res.in)

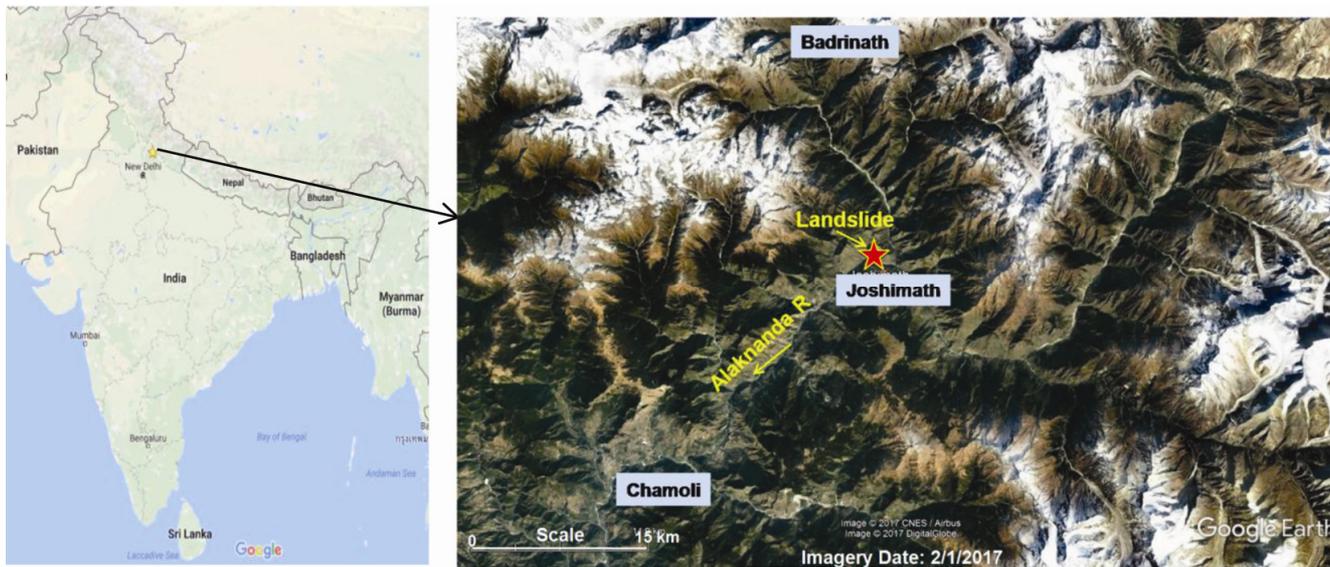


Figure 1. Location of the landslide at Vishnuprayag near Joshimath, Uttarakhand, India.

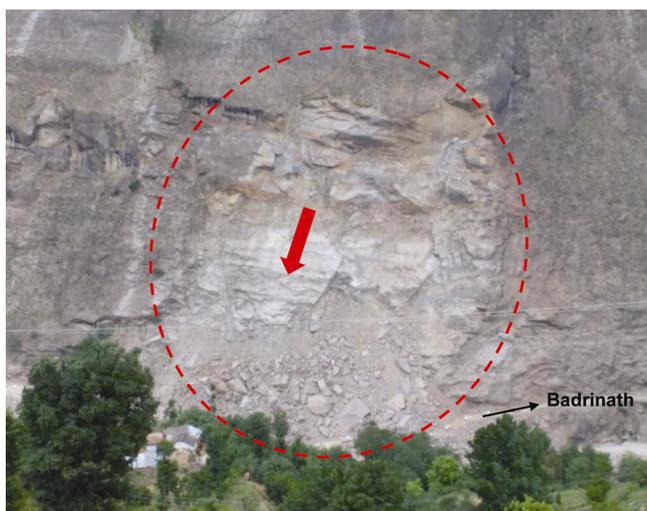


Figure 2. Panoramic view of the landslide.

The rainfall data during this period did not show any significant rain which could have triggered the slide. The slide may have been triggered due to the opening up of cracks present in the rock mass and probably aided by some water seepage through fractures as a few wet patches were observed on the upper part of the hill.

In an earlier study, an area of about 1 km road sector of the hill was predicted as landslide potential high hazard zone². At that time, the area had already two distinct landslide potential slopes involving rock fall and rockslide along major discontinuity plane. The present landslide also occurred in the same hazard zone.

In the present scenario, the hill is highly prone to landslides, as there are at least three vulnerable unstable slopes which are posing threat to road and traffic, particu-

larly during rainy season. The landslide risk areas are highlighted in Figure 5 by combining the high hazard zone identified in an earlier study² and the landslide events that occurred in 2015 and 2017. Rockfall does not affect a large area, but can be fatal for the traffic entrapped in the rockfall zone. Sometimes the initiation of rockslide or rockfall goes unnoticed because of the steep hill and there is no time to give any warning.

Stability analysis of a landslide is essential to evaluate its present stability condition and to suggest adequate remedial measures. Basically, shear strength along the critical slip surface governs the stability of the slope section. The mobilized shear strength along any slip surface of a $c-\phi$ material can be expressed by the Mohr–Coulomb failure criterion. Here, any effect from the intermediate principal stress is neglected. The Mohr–Coulomb criterion holds good for both rocks and soils under shearing and compression. The shear strength of a soil or rock interface may be defined by as

$$\tau = c' + \sigma_n \tan \phi'$$

Here, τ and σ_n are the shear strength along and the normal stress on the failure surface respectively, at the time of failure; c' and ϕ' are the effective cohesion and effective internal angle of friction at drained condition respectively.

In the present study, a two-dimensional finite element analysis for assessing the stability status of the landslide was carried out in Phase 2, 8.0 software platform. For this, shear strength reduction (SSR) technique⁵ was implemented in which the Mohr–Coulomb parameters (cohesion and internal angle of friction) of the slope materials were reduced by a factor called the strength



Figure 3. Landslide boulders and debris on the road and in the Alaknanda valley.

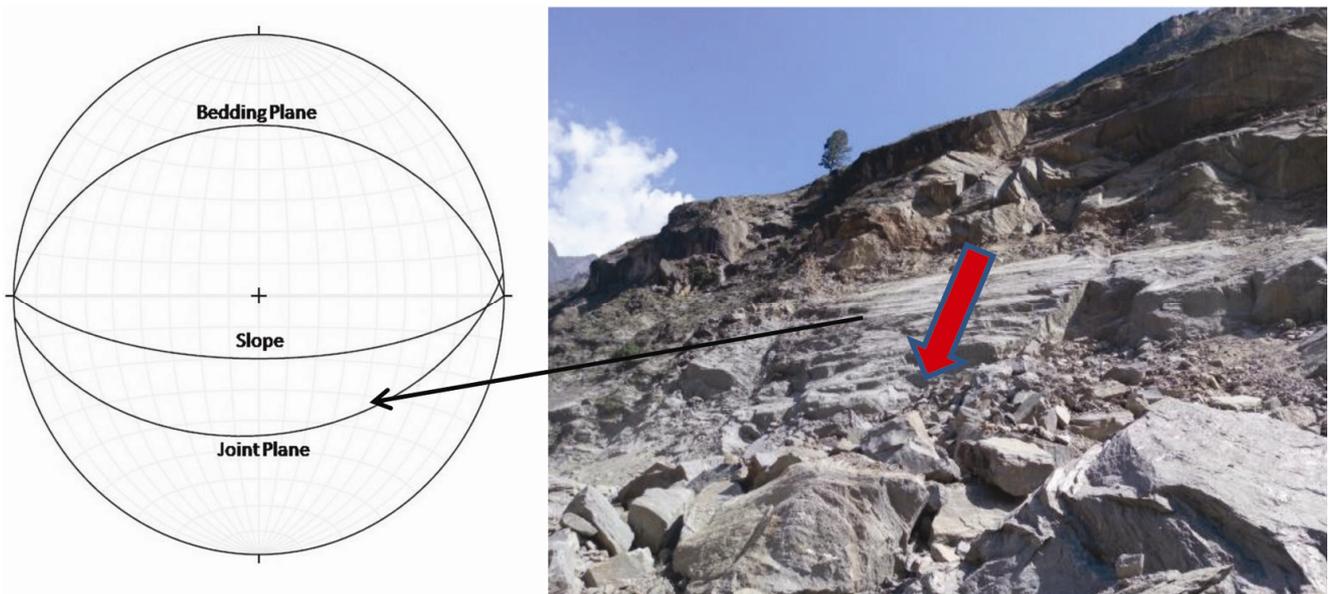


Figure 4. Planar failure along the outwardly dipping joint.

reduction factor (SRF), and the factor of safety of the slope was determined for each phase of the finite element stress analysis. The analysis was repeated for different values of SRF; until the model became unstable. This ultimately determines the critical SRF, or safety factor of the slope⁶.

As can be seen from Figure 6, the slope was modelled with two layers: (i) debris portion at the toe of the slope, and (ii) rock portion with two rock discontinuity sets in the rest of the slope. From field visits, it was observed that the landslide had taken place along the major discontinuity plane inclined at 45° at a spacing of 0.75 m (joint set 1) and was in the daylight of the slope face dipping. This prominent discontinuity plane caused the planar failure of the rock slope. The bedding joint set was in-

clined at 35° into the slope face and spaced at 1.5 m (joint set 2). The geotechnical properties of the slope materials and rock joints were estimated from the laboratory tests and relevant literatures (Table 1)^{7,8}. For stability analysis, a uniform meshing was chosen with six-noded triangular elements in the domain. The boundary conditions for the domain were taken as follows: (i) roller supported on the side edges, and (ii) hinge supported at the bottom. The results of the analysis showed that the existing untreated slope had factor of safety (FoS) of 1.05 in dry condition under static loading, whereas the slope failed with FoS of 0.94 under a pseudo-static loading condition considering seismic activities (horizontal and vertical seismic acceleration coefficients determined according to IS 1893 (Part 1): 2002 for zone V seismic region). These slope



Figure 5. Landslide risk areas of Hathi Pahar at Vishnuprayag on NH-58.

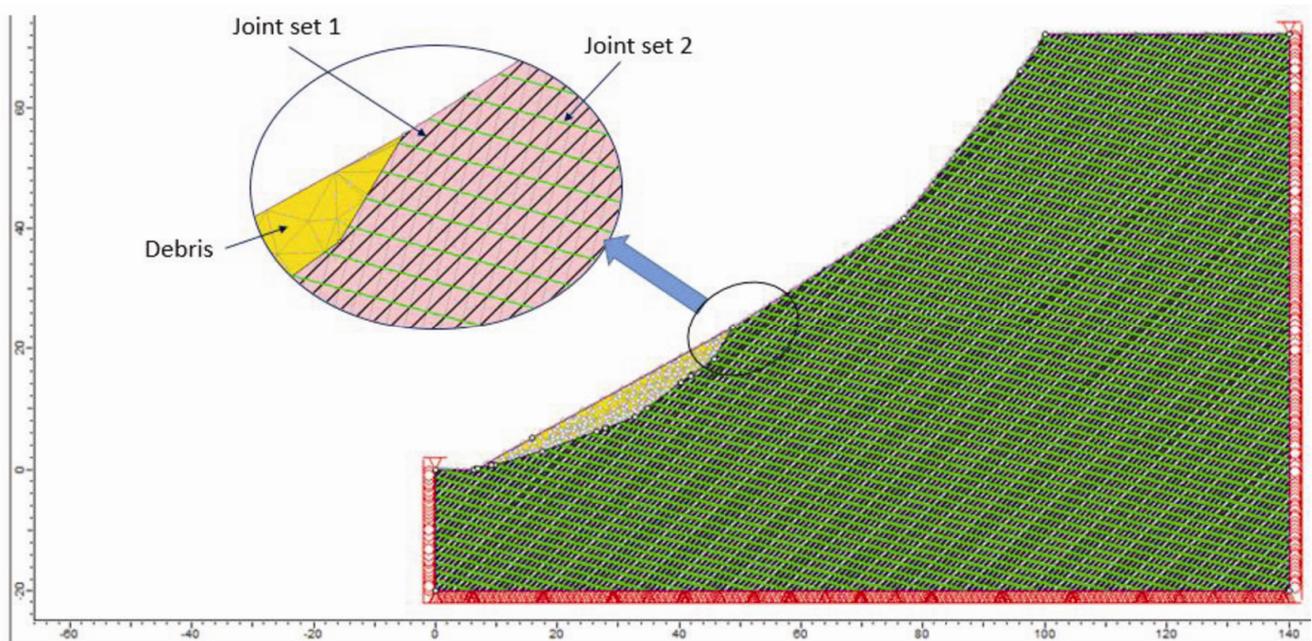


Figure 6. Geometry of the present slope.

stability analyses suggest that the present slope if left untreated may fail – in future in the event of an intense rainfall or due to a strong vibration during earthquake in the area. The debris part has been found to be critical with a maximum total displacement of 18.2 cm in case of static loading and 25.8 cm in case of pseudo-static loading (Figure 7).

To stabilize the landslide, appropriate control measures are required to be taken on slope face. One of the best-

suited measures could be rock bolting and replacement of some parts of the debris using plain cement concrete (PCC) to arrest further sliding (Figure 8). Hence, slope stability analysis was performed with a small portion of debris being replaced by PCC (elastic modulus = 41 GPa, Poisson's ratio = 0.2, peak cohesion = 4.98 MPa, peak internal angle of friction = 37°, compressive strength = 20 MPa). In addition, fully grouted rock bolts (length = 12.0 m and diameter = 20 mm) may be installed normal

Table 1. Material and joint properties used for slope stability analysis

Description	Elastic modulus (GPa)	Poisson's ratio	Peak cohesion (MPa)	Peak internal angle of friction	Dilation angle
Debris material	2.0	0.30	0	16°	10°
Gneiss (intact rock)	30.0	0.27	28.5	28°	5°
Rock discontinuity	0	500.0	185.0	0	20°
	Tensile strength (MPa)	Normal stiffness (MPa/m)	Shear stiffness (MPa/m)	Peak cohesion (MPa)	Peak internal angle of friction

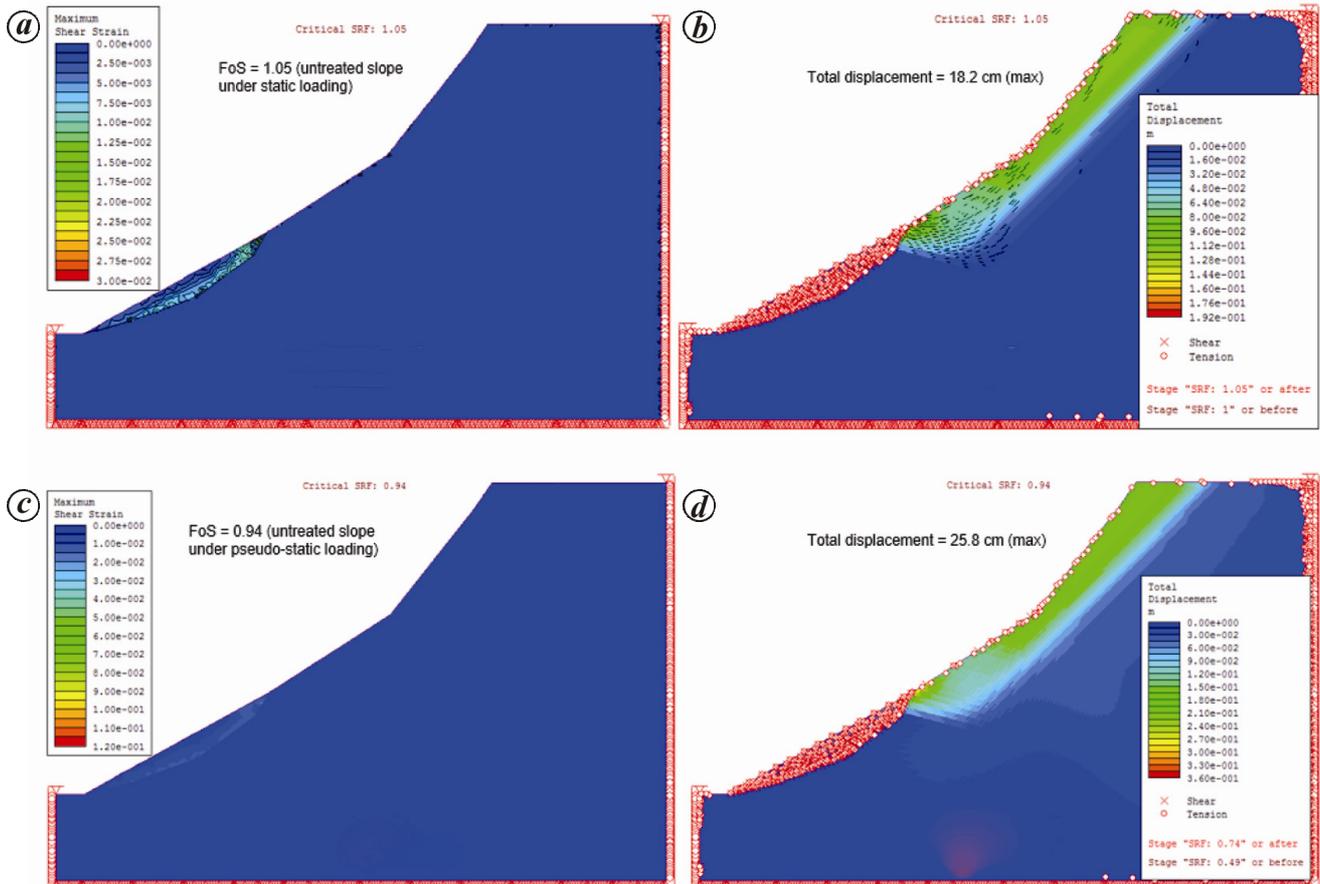


Figure 7. Slope stability analysis of the untreated present slope. (a, b) For static loading: (a) Maximum shear strain and (b) Maximum total displacement. (c, d) For pseudo-static loading: (c) Maximum shear strain and (d) Maximum total displacement.

to the boundary section at a spacing of 0.5 m × 0.5 m, with mechanical properties such as elastic modulus of 200 GPa and tensile capacity of 100 kN. The analysis results were interpreted and the slope was observed to possess a global stability factor of 1.18 and 1.05 for static and pseudo-static loading respectively. On the other hand, the rock-bolted portion was found to have a minimum FoS of 3.17 and 2.64 for static and pseudo-static loading respectively. Hence, the slope treated with rock bolts and concreting can be considered as stable (Figure 9 a). The debris portion further needs wire-mesh netting, if possible, to arrest any rockfall probability in future,

since the maximum total displacement after rock bolting and PCC was determined to be 16.2 and 18.1 cm for static and pseudo-static loading respectively (Figure 9 b).

There are various techniques which are generally used to prevent rock slides and protect against rockfall. The following control measures could be considered to minimize the sliding activities in future:

1. Removal of loose boulders by dressing of slope.
2. Rock bolting can be used to pin individual rock blocks and tensioned rock bolts are installed across potential failure surfaces and anchored in sound rocks. This improves the overall stability of the slope. FEM

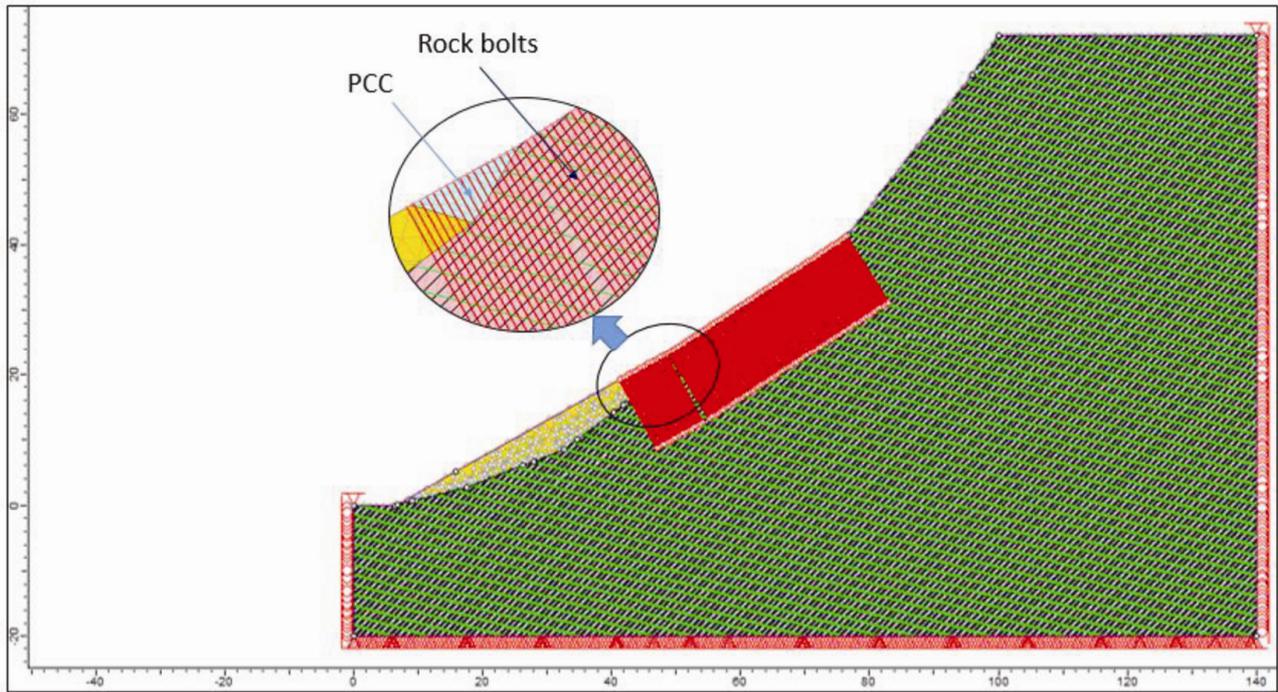


Figure 8. Slope geometry along with rock bolts and plain cement concrete (PCC) filling.

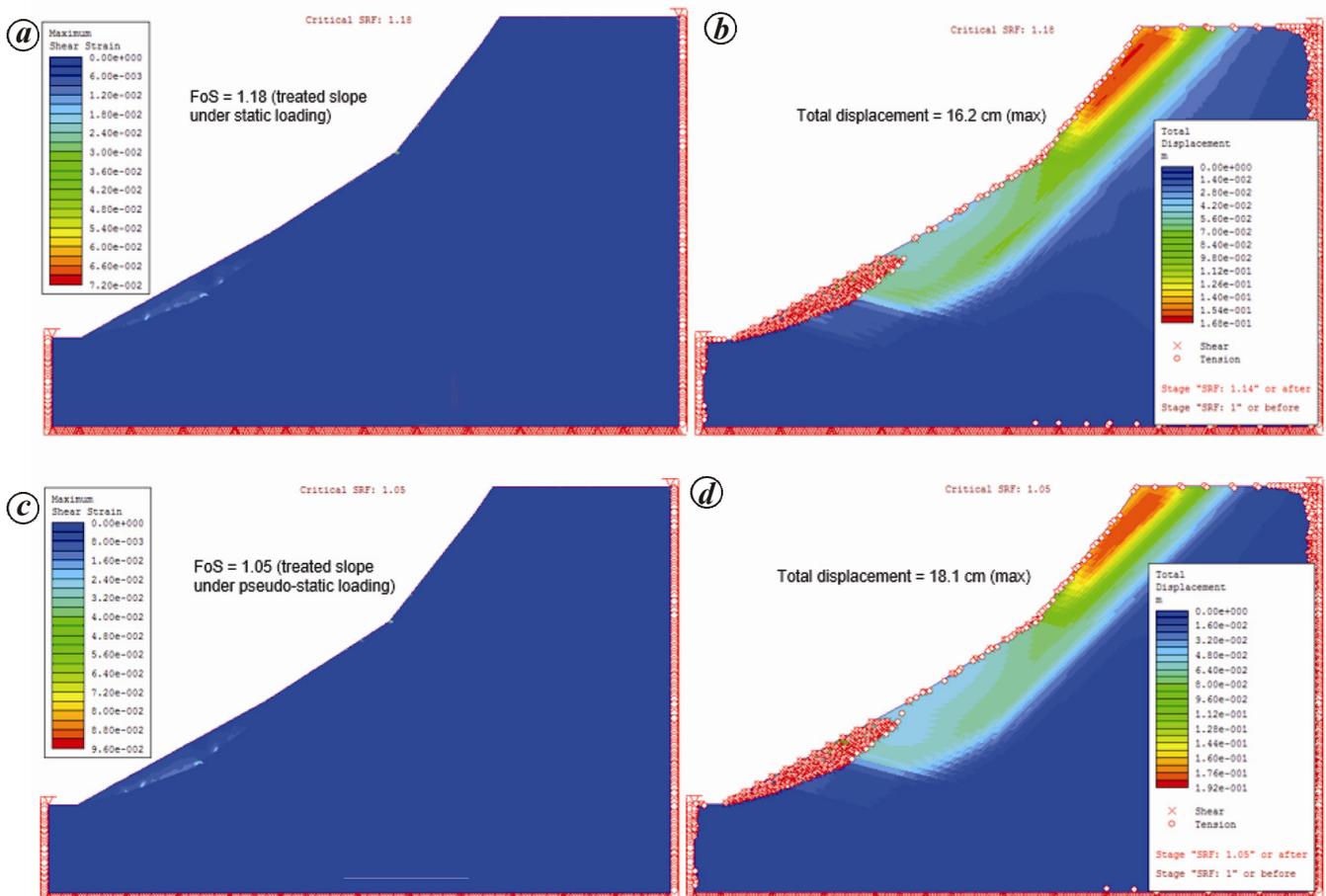


Figure 9. Slope stability analysis of the treated present slope. (a, b) for static loading: (a) Maximum shear strain and (b) Maximum total displacement. (c, d) For pseudo-static loading: (c) Maximum shear strain and (d) Maximum total displacement.

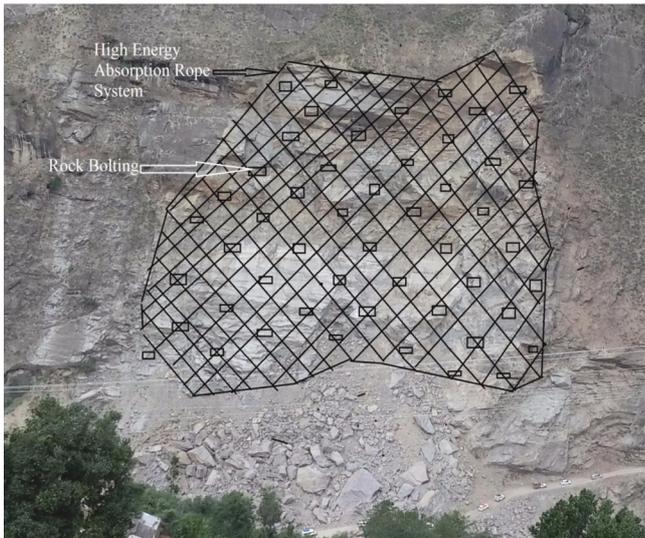


Figure 10. Wire netting with high energy absorption rope system to protect against rockfall.

analysis in the present study has also substantiated the same by achieving a higher safety factor with rock bolts of diameter 20 mm and length 12.0 m installed on the slope face at a spacing of 0.5 m.

3. Wire netting with high energy absorption rope system (Figure 10) maybe applicable for slopes having highly jointed and fractured rock mass to prevent and intercept falling rocks to rest on the slope and reduce the speed for large blocks so that they may be retained by other counter measures on downhill slope.

4. Rockfall barrier at toe to form a rigid barrier to intercept free-falling rocks which can prevent the rock boulders from reaching the road, however, this is applicable where sufficient space is available at the roadside.

5. Due to the presence of steep slope in the present case, rock shed as a passive protection method may be used for protecting traffic from rockfall. It generally consists of a reinforced concrete slab covered with the ground embankment and supported by specially designed support systems to dissipate the impact energy of the rockfall⁹.

However, a detailed investigation is required before prescribing suitable measures along with the engineering design to arrest the landslide.

It is inferred from the field investigation and previous studies that the study area is prone to landslides and rockfall. Road safety is a major concern due to its strategic and religious significance. The stability analysis shows the marginal stability condition of the slope and the FoS may decrease below a value of 1 as a consequence of major rainfall events, earthquake and/or any unplanned human interference. A few possible measures, viz. rock bolting, wire netting and rock sheds have been suggested. It is recommended that the hill should be continuously

monitored through proper surveying and instrumentation such as total station, laser mapping, wire extensometers, etc. This will help predicting the initiation of any failure, particularly during the monsoon period so that proper warning can be issued before any major event occurs. Further, the site should be studied in detail involving discontinuity mapping, geotechnical characterization of rock mass and more in-depth stability analysis, so that adequate control measures with proper design could be suggested.

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