Hill slope stability examination along Lower Tons valley, Garhwal Himalayas, India

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ABSTRACT
The present research details the remote sensing, geotechnical and seismic aspects of hill slopes in Lower Tons river valley, Garhwal Himalaya, India. The region is a part of Lesser Himalaya and holds religious and strategic importance. The studied span has been a site of slope failures in the past. The remote sensing investigation was used to characterize the geomorphological and hydrological attributes of the area. This information was used to delineate vulnerable locations. Along the road stretch of about 80 km, 80 tests were conducted to ascertain the soil particle distribution and plasticity indices; and 33 tests for shear strength properties. Using the geotechnical parameters, numerical simulation was conducted for two slopes of angle, 40° and 50°, with a consistent height of 50 m. Most of the slopes were stable at an angle of 40°, however, 30.30% (FEM) and 24.24% (FDM) of the analysed slopes failed for the steeper slope. Eventually, the pseudo-static analysis was done. The inclusion of seismicity increased the incidences of slope failure by 33.33% and 39.39% for the slope with an inclination of 40° and 50°, respectively. Afterwards, the slopes were optimized for their critical angle as a function of the safety factor.

1. Introduction
The present research deals with the geomorphological and geotechnical aspects of the Lower Tons valley, Garhwal Himalaya, contingent upon which is the stability of the vulnerable and fragile hill slopes. The steep summits of the Garhwal Himalaya...
are contained in the most active tectonic region of the planet, leading to constant uplift and seismic episodes (Matte et al. 1997). Slope failure is a function of geospatial, hydrological and stress regime of the region (Zare et al. 2013; Chakraborty and Goswami 2017). Slope failures can have devastating effects on lives, economy and infrastructure in the region (Althuwaynee and Pradhan 2017). The damages are not just tangible but an array of intangible losses also exist. Unscientific and haphazard construction and excavation operations are usually the precursors for failures in these fragile hilly terrains (Barnard et al. 2001). However, in order to provide a quality life for the local residents, it is imperative to undertake and execute these infrastructural projects at an ever-increasing rate (Raman and Punia 2012). Moreover, the strategic importance of the Himalayan terrain necessitates the government to construct highways, railway tracks, bridges, and tunnels (Mahanta et al. 2016). Annual losses due to slope instability, both rainfall- and seismically induced, in the Himalayan region amount to the tune of one billion US dollars (Naithani 1999; Weidinger 2006).

Geotechnical field investigation of vulnerable slopes in these lofty regions are cumbersome and expensive, hence remote sensing and GIS tools can be of great help (Saha et al. 2005; Pandey and Sharma 2017; Ambrosi et al. 2018). Remote sensing and GIS techniques ease the spatial data analysis of inaccessible areas through different thematic maps (Pandey et al. 2008). These techniques can easily enumerate the myriad geometric-morphometric-lithological and environmental factors affecting the stability of slopes (Sharma et al. 2014). These tools also provide the luxury to keep real-time record of temporal and spatial variations occurring within the valley (Squarzoni et al. 2003). Correlation of ground truth and GIS data results in landslide susceptibility mapping, which is useful for further geotechnical studies of landslide prone areas and their mitigation. Eventually, this information collected using morphometric data and thematic maps can be validated through field investigation. In the present research, the inputs of remote sensing and GIS studies have been employed in the numerical assessment of the hill slopes along Lower Tons valley region. Furthermore, we have also conducted pseudo-seismic analysis to ascertain the stability in case of an earthquake event.

In earlier days, most of the geotechnical researchers had to rely on the limit equilibrium methods (LEM) for slope stability investigation (Liu et al. 2015). The calculation of factor of safety (FOS) in LEM involves assumption of a failure surface; the slope mass above this pre-defined surface is divided into numerous thin columns and all the inter-columnar forces are calculated to predict stability (Kainthola et al. 2015a; Hazari et al. 2020). Factor of safety (FOS) is a quantitative approach used to recognize how stronger shearing forces are relative to driving forces (Kainthola et al. 2015b). However, the inability of LEMs to incorporate the complex geometries and anisotropic lithologies demands a sophisticated and advanced techniques to assess slope stability and hence the numerical tools came into prominence (Starfield and Cundall 1988). Numerical methods, apart from the FOS calculation, offer robust visualization of different geotechnical aspects before, after and during slope failure events. These techniques can also easily simulate the effect of seismic and rainfall events in slope stability analysis.
The present research examines the slope instability analysis using finite element method (FEM) and finite difference methods (FDM) (Mansour and Kalantari 2011; Singh et al. 2016). FEM undertakes the stability analysis by allocating the slope model into numerous minor elements and accordingly makes essential stress-strain arithmetic in these elements using matrix form equation, while equations of FDM are solved in small time steps as current stress-strain are projected using previous time step (Kainthola et al. 2013). The wide acceptance and intelligible analysis are the prime factors for adopting these two numerical techniques in the present research work.

To achieve the results of the slope stability analysis, soil samples were collected after an exhaustive field survey and their geotechnical and geo-mechanical properties were discerned in the laboratory. The study takes up geotechnical properties viz., grain size analysis, plastic limit, liquid limit, cohesion, and angle of internal friction for characterization of the material. The present study details the factor of safety (FOS) of slopes for slope angle 40° and 50° both using FEM and FDM. Incidents of earthquakes reduces the geotechnical properties of the slope mass and hence pseudo-static stability analysis was performed using FEM to evaluate the stability in a seismic event.

2. The study area

Tons valley is a geomorphic and geologic unit of Garhwal Himalayan lying between the Indian states of Uttarakhand and Himachal Pradesh and occupies an area of nearly 5145 km² (Figure 1a). The altitude ranges between 426 m and 6284 m, above the mean sea level (msl). Local tectonics and morphology lead to swift weathering and erosion of the region, rendering high relief variation. The river Tons originates from the right flank of the Bandarpunch glacier approximately at 5200 m above msl and make its way through a narrow valley for a distance of about 200 kms to meet the Yamuna river at Kalsi town (Pankaj et al. 2012). The past tectonic forces have given rise to asymmetrical folding, reverse faulting, and thrusting and hence the local and regional drainage patterns are controlled by the existing lineaments, lithological structures and the prevalent tectonic features (Holbrook and Schumm 1999).

Geologically, the area extends from the Lesser Himalaya in the south to the Higher Himalaya in the north. Presence of folds, faults, fractures, and other discontinuities within the valley are the proxies to decipher the past tectonic movements. In the northern part higher-crystalline rocks are covered by glaciers whereas, in the southern part sedimentary rocks dominate in the valley. Strata of Tejam-Damta-Jaunsar-Mussoorie-Sirmur-Sivalik-Vaikrita-Almora-Ramgarh Groups are evident stratigraphical units in the Tons valley, Garhwal Himalayan region (Figure 1b) (Auden 1934; Rupke and Sharma 1974; Valdiya 1980; Thakur and Rawat 1992).

The region sees high incidences of slope failures during the monsoon season, as the inclusion of water leads to a drastic reduction in the geotechnical attributes of the slope material. The area of interest receives precipitation in the form of snow and rain. During monsoon season, the area receives good rain, however, little rain is received in the winter season which is in the form of snow (Figure 2). Winter
precipitation occurs due to the western disturbances that pass over the north-west part of the India during the months of December to February (Semwal and Dimri 2012). The climate of the study area is generally temperate i.e., warm in summer (March to mid-June), humid during monsoon (mid-June to September), and cold in winter (October to February). Relative humidity is high in the monsoon (rainy) season, up to 80%, which reduces progressively and diminishes during summer.

A large number of slope failures along the road were observed during the field visit. Figure 3a shows the crown portion of the landslide above road level, which is comparatively small as compared to the failure zones beneath the road level. The rock material was phyllitic and it is thoroughly crushed, and along the road level serrated pattern can be seen. Below road level, two parallel zones of depletion can be observed. The site also consists of fragmented debris, depicting a downward movement, at places these have been stabilized using gabion walls (Figure 3b). Some of the

Figure 1. (a) Tons valley, Garhwal Himalaya, India. (b) Regional geological setup of the study area (modified after Thakur and Rawat 1992). (c) Elevation map along with evident landslide locations in the study area. (d) Drainage distribution pattern of the area of interest.
Figure 2. Monthly rainfall trends for Uttarkashi from 01-Jan-2018 to 30-Oct-2020 (Source: India-WRIS 2020).

Figure 3. Existing slope failures along the road from the study area.
failures, especially in foliated rocks show signs of structurally controlled instability (Figure 3c). Presence of vegetation cover on the slope indicates its inactivity. A major number of the failures are governed and controlled by the slope angle and the shear strength of the soil mass (Figure 3d). However, post-impact crushing of rocks can lead to fragmentation. The failure along these slopes causes periodic disrupt in traffic. The rate of deformation in some of the slopes is slow while in steeper slopes its rather rapid. Most of the minor failures are a part of major landslides zones in the area.

3. Remote sensing and GIS studies

The study area includes rugged topography, folds, faults, river channels, glaciated peaks and forests that make the field investigation rigorous, time consuming and perilous. With the advent of latest development in remote sensing and GIS, one can decipher the prominent geomorphological and geological features of the study area. Furthermore, remote sensing empowers us to develop thematic layers of elevation, slope, slope aspect, land use/landcover, forest cover, and drainage pattern distribution of the study area. These base maps enable quick visual examination of various morphometric features and accurately determine the environmental conditions prevailing in the study area (Al-Saady et al. 2016). These tools also keep a spatial and temporal record of changes occurring on the surface and near surface, which are an invaluable asset to understand long-term landslide phenomenon. Faults, scarps, and any disturbances in the natural ecosystem that will a clear indication of landslide hazards in the study area can be discerned through these tools. LISS IV (5.8 m, 12 December 2011) and LISS IV (5.8 m, 1 December 2013) data were used for accessing satellite imageries to construct various thematic layers.

A landslide inventory generated between Haripur to Minas shows landslide locations as well as towns in the near vicinity (Figure 1c). Morphometric attributes represent a simple approach to define basin processes and the associated characteristics. Anthropogenic changes have led to widespread modifications in physical structure of rivers, biotic communities and ecological functioning of aquatic ecosystem around the world (Thomson et al. 2001). Since, these aspects have a direct bearing on the stability of hill slopes, morphometric techniques were applied to gain a better understanding of the prominent drainage network features.

Based on the GIS examination, the study area has been marked into several elevation zones (Figure 1c). The Tons basin consists of dendritic, parallel, and rectangular drainage patterns (Figure 1d). The climate type of the area includes, sub-tropical temperate to sub temperate. At lower elevation the region supports rich forest of Pinus (Chir), which merge at higher elevations into Cedrus (Deodar) and Spruce mixed with Oaks and other broad-leaved species. In general, the change in temperature with the elevation has its influence on the growth and variety of natural vegetation. The area under study experiences a diversified and rich natural vegetal cover. Thus, the varied surface conditions and variations in attitude and climatic conditions have resulted in the varied type of vegetation in a particular attitudinal zone. This aspect directly influences and controls the stability and erosion of slopes.
Tons valley was delineated on the basis of hill slope inclination into five groups i.e., very gentle (<15°), gentle (16°–25°), moderate (26°–35°), steep (36°–45°) and very steep (>46°) representing an area of 13.82%, 26.69%, 28.42%, 22.24% and 8.83%, respectively. Steeper inclination of hill cut slope is a leading factor for instability and can exacerbate failures. The slope aspect also affects the moisture and temperature, since it will specify the amount and time of sunlight directly received upon the slope mass (Srivastava et al. 2010). Therefore, slope aspect plays a significant role in the stability analysis of the study area. Land use/land cover is considered as one of the factors influencing landslide susceptibility, since erratic anthropogenic disturbance is an antecedent to slope deformation. Total seventeen land use/land cover class are identified in the study area. Most of the area is occupied by evergreen forest, grass/grazing land and glacier. The other classes like agriculture-fallow land, waste land, river, scrub forest, forest plantation, rural built-up, lake and water bodies are validated with the BHUVAN WMS Service & Land use/Land cover Atlas NRSC (2010).

3.1. Linear parameters

The linear parameters are an indispensable aid to geomorphologically characterize a valley and includes stream order, stream number, stream length, mean stream length, bifurcation ratio, mean length ratio, perimeter and weighted mean bifurcation ratio. The perimeter of the drainage basin boundary is determined to be 443.91 kms. The stream order is a dimensionless number, which can be used for the evaluation of geometry for drainage networks on dissimilar linear scales. The drainage network of the Tons valley is classified into eight stream orders (Figure 1d) (Strahler 1954). Slope failure events are significantly affected by high stream order, whereas its importance decreases with reduction in the stream order (Fan et al. 2013; Raja et al. 2017). The maximum frequency for the first order stream is 16,374 and there is a decrease in stream frequency as the stream order increases (Figure 4) (Horton 1945). Congruently, the GIS study reveals that the total length of stream segments is maximum for first order streams, it decreases as the order increases, and is lowest for the highest order streams in almost all the tributary basin of the Tons Valley. The highest stream length is of the sub basin of Pabar (6897.28 km) and the lowest length is of Amtyar gad (207.00 km).

3.2. Areal parameters

The areas of each watershed lying in the study area have been calculated and it was found that Amtyar Gad is the smallest with an area of 41.5 km² and Upper Tons is the biggest watershed with an area of 1994 km². Stream frequency for the study area varies from 2.91 to 5.88. On investigation of stream frequency, lowest value of stream frequency is found in Upper Tons which possess low relief and highly permeable geology. While, the highest value of stream frequency is noticed in Nira Gad, where high relief condition prevails, impermeable sub-surface material and sparse vegetation. In literature it is said that a higher stream frequency reflects greater surface run-off and a steeper ground surface. The drainage density value ranges from 3.91 to 6.93
in the valley. This range is suggesting very coarse to fine drainage texture. The drainage density is an important indicator of linear scale of landform elements in a stream-eroded topography. An increase in drainage density has been correlated with higher instances of slope collapses (Hasegawa et al. 2013). It has further been observed that low drainage density can lead to deep rooted landslides & conversely a number of shallow slides are generated due to higher drainage density (Onda 1993). The shape and size of the basin can conceivably affect the stream discharge and volume of rainwater received and hence, the total run off.

4. Geotechnical studies

The collected samples were brought to the laboratory to test them for their grain size distribution, Atterberg limits and strength parameters in their bulk state. The tests were done in compliance with BIS and ASTM standards (Holtz et al. 1981; Ranjan and Rao 2007). Eighty samples were tested for Atterberg limit and gain size distribution pattern analysis. However, 33 soil samples were chosen from the sample set for further analysis of their deformational parameters, eventually used for numerical simulation.

4.1. Grain size analysis

Grain size distribution pattern is acquired using sieve analysis. Grain size variation within the soil samples helps to predict compaction, porosity, permeability, as well as
its load bearing capacity. These geotechnical parameters further help to assess the pore water pressure and liquefaction potential of the soil masses which will be crucial to understand the stability of slopes (Matsuura et al. 2008; Shah et al. 2020). To evaluate sieve analysis, soil samples were passed through sieves of different mesh sizes (arranged in descending order from top to bottom) by mechanical shaking for 10 minutes. Soil weights retained by all the sieves and eventually their cumulative percentages retained at each level is calculated to assess percentage fines for each sieve size. Analysis for 80 soil samples was done using the sieves of mesh sizes of 4 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, 0.063 mm and 0.01 mm. The holistic grain size distribution of the Lower Tons valley depicts high prevalence of coarse sand size grains which are poorly sorted or well graded (Figure 5). These types of soils possess low permeability and high compaction potential. The eclectic range of sizes in soil can be attributed to the high energy environment and limited transportation.

4.2. Atterberg limits

Water content of soil has a significant effect on its geotechnical properties. Porosity, permeability and infiltration capacity are the inherent geomechanical properties of soil mass that defines the water content. The amount of water content is also affected by the geological, hydrological as well as the prevalent rainfall regime. The physical behaviour such as solid, semi-solid, plastic and liquid state of the soil mass depends on its water content. The amount of water present in the pore spaces invariably leads to reduced shear strength of the soil and hence affects its stability.
Variation in water content alters the physical state of the soil mass and the limits of these changes are called Atterberg limits, named the discoverer (White 1949; Seed et al. 1966). The geotechnical parameters such as liquid limit and plastic limit are the minimum water content at which soil sample begins to show liquid or plastic properties respectively. Earlier workers also have positively established the quantitative relation between shear strength with their liquid and plastic limits of the soil sample, i.e., the average value of shear strength is 1.7 kPa at liquid limit and 170 kPa at the plastic limit (Sharma and Bora 2003).

Liquid limit and plastic limit of 80 soil samples were ascertained using Casagrande’s apparatus and thread-rolling test, respectively; and the arithmetic difference of these geotechnical properties yield another useful parameter known as plasticity index. On careful examining the results of these Atterberg limit values, one can easily mark that at some places plastic limit exceeds the value of liquid limit and these are the characteristic of dominantly sandy soils (Figure 6). Deeper understanding of the soil behaviour can be gauged through the statistical distribution of the data (Figure 7). The average liquid limit, plastic limit and plasticity index are 23.3, 19.5 and 5.4, respectively, while their respective median values are 22.5, 14.3 and 4.1. Based on these values, the soils can be generally classified as low plasticity silty soils, ML as per ASTM classification.

5. Stability analysis

The study area is a famous tourist spot among domestic and foreign tourists and the local residents mostly rely on them for their livelihood. Every year thousands of tourists visit the valley and enjoy river rafting, trekking, site seeing etc. In order to facilitate the local economy and attract tourists from different parts of the world, a major impetus to the civil construction (roads, bridges and tunnels) in the last decade has been emphasized (Sundriyal et al. 2018). However, on a critical review of the past
slope failure events, it became crucial to assess the slope stability before and after laying the foundation of any major civil infrastructure in the valley.

To ascribe the slope stability scenario of the study area a robust field investigation was complemented with remote sensing study. Representative soil samples were collected from 33 different locations and their geotechnical parameters were decoded in laboratory (Figure 8). Apart from physical and deformational properties, direct shear testing was used to shed light on their cohesion and angle of internal friction of soil masses; and their outcomes are statistically embodied (Figure 9). The averaged unit weight, Poisson’s ratio and Young’s modulus for the soil masses prevailing in the study area have been listed in Table 1.

Figure 7. Atterberg limits of all the soil samples of the study area (LL = Liquid Limit, PL = Plastic Limit, PI = Plasticity Index).
Figure 8. Satellite image of the soil sampling location.

Figure 9. A violin-plot of cohesion and angle of internal friction ($\phi$) obtained for soil samples using direct shear testing.
Slope geometry is a dominant factor that affects slope stability of any area and in field investigation and remote sensing studies slope geometry was of prime importance. However, it is rather difficult to gain exact geometry (slope angle and slope vertical height) of all the vulnerable slopes present in the study area without availability of sophisticated instruments like total station. Therefore, for the sake of simplicity and practicality, a similar slope geometry with a vertical height of 50 metres and slope angles of 40° and 50° were modelled to accommodate a larger vulnerable area. These two slope angles were chosen for the numerical analysis, since these two inclinations were the most common for the hill cut slopes in the research area. All the slope parameters affecting its stability excluding dynamic factors (i.e., ground water conditions, rainfall events and seismic activity) are fed in the FEM and FDM based software programs and factor of safety (FOS) is evaluated for 33 studied locations. Apart from FOS, visual examination of displacement distribution and strain distribution is facilitated through numerical (FEM and FDM) modelling.

5.1. Simulation

The vulnerable zone for the selection of road stretch for stability analysis of hill slopes was ascertained based on the remote sensing examination. Lower Tons valley contains the high drainage density, making it more prone to shallow failures emanating due to surficial alluvial or colluvial material. Slope stability is evaluated using finite element method (FEM) and finite difference method (FDM) techniques, however both techniques rely on shear strength reduction (SSR) approach following the Mohr–Coulomb failure criteria (Matsui and San 1992; Cala and Flisiak 2003; Diederichs et al. 2007). Since the amount and nature of deformation can be easily visualized and quantified in these tools, they were preferred over traditional tools (Duncan 2013). Mohr–Coulomb failure criteria is a linear constitutive model best suited for homogenous soil like material (Labuz and Zang 2012).

In the SSR techniques, a new definition for FOS was coined that is the minimum factor required to divide original shear strength of rock mass until the slope becomes unstable (Duncan 1996). Hence, both FEM and FDM achieve factor of safety (FOS) by reducing the shear strength of soil/rock mass until the condition of slope failure arrives (Dawson et al. 1999). In other words, cohesion and angle of internal friction are simultaneously and continuously weakened, multiple times by a factor (strength reduction factor or SRF) until the slope instability arrives to the condition as given in Equations (1)–(6) (Zhao et al. 2015; Tiwari et al. 2020).

\[ c' = \frac{c}{SRF}, \]

### Table 1. Mean soil sample physico-mechanical parameters.

| Geotechnical properties     | Values       | Standard deviation |
|-----------------------------|--------------|--------------------|
| Unit weight                 | 2200 kg/m³   | 150                |
| Poisson’s ratio             | 0.29         | 0.02               |
| Young’s modulus             | 1000 MPa     | 300 MPa            |
\[
\phi' = \tan^{-1}\left(\frac{\phi}{\text{SRF}}\right),
\]  

where \(c\), \(\Phi\), \(c'\) and \(\Phi'\) are the cohesion, angle of internal friction, factored cohesion and factored angle of internal friction of the soil samples, respectively,

\[
FOS = \frac{\tau_f}{\tau},
\]

\[
FOS = \frac{c + \sigma \tan \phi}{\tau},
\]

\[
FOS = \frac{c + \sigma \tan \phi}{c' + \sigma \tan \phi'},
\]

\[
FOS = \text{SRF},
\]

where \(\tau_f\) is the available shear strength, \(\tau\) is acting shear stress, and \(\sigma\) is the normal stress acting on the failure plane.

The stability analysis using FEM involves selection of appropriate element type, mesh types with a suitable number of elements. The accuracy of numerical analysis will increase with an increase in the number of elements in the model; however, the computation process will take a little longer time than usual on increasing the number of elements (Griffiths and Lane 1999). In the present work, 1500 uniform-6-noded triangular elements (3 at each vertex and 3 at the centre of each side) were employed in FEM study. These elements are better at incorporating the complexities of slope geometry and material in the model. The number of elements were fine tuned based on the factor of safety calculations.

The gravity field stress type was ascribed in slope models to simulate well with real ground scenario. In the constitutive slope models for finite element analysis the field stress and body force are the initial loading element along with isotropic elastic type and plastic material type. Peak cohesion and peak angle of internal friction were determined for 33 soil samples in the laboratory and applied to the constitutive slope models. In view of the study area and earlier literatures, residual cohesion and residual angle of internal friction were taken to be 50% and 70% of their peak values respectively (Renani and Martin 2020). Similarly, same geometry and material properties were used to assess slope stability following the FDM. The total displacement and maximum shear strain distribution pattern based on FEM; and shear strain-rate based on FDM was examined along with failure surface (Figure 10).

**5.2. Pseudo-static seismic analysis of slopes**

The movement of Indian plates towards Eurasian plates led to evolution of Himalaya, and to accommodate tectonic forces in brittle lithospheric plates, a number of major and minor faults developed (Yin 2006). The continuous movement of lithospheric plates accumulates a significant amount of strain energy within the elastic rocks, and
as the strain energy exceeds the tensile strength of the rocks, the earthquakes are felt. Every year the Himalaya records a few earthquakes of either smaller or greater magnitude and weakens the rock mass strength by loosening of intact soil or initiating the formation of discontinuities within the rock mass. These sudden shaking in the Himalayan region have a proclivity to deter the health of slopes, and this necessitates the incorporation of seismicity in slope stability assessment. Generally, the numerical methods offer integration of seismicity in stability analysis based on pseudo-static and pseudo-dynamic approaches. However, in the present study pseudo-static approach was implemented using FEM. On rigorous examination of previous earthquake records in the Himalayan region, the literature suggests 0.15 as the value of horizontal seismic coefficient ($K_H$) to be employed in the present of work to carry

**Figure 10.** Outcomes of numerical simulation at a location in the study area: (a) total displacement distribution at $\beta = 40^\circ$ (FEM); (b) maximum shear strain distribution at $\beta' = 40^\circ$ (FEM); (c) maximum shear strain-rate distribution at $\beta = 40^\circ$ (FDM); (d) total displacement distribution at $\beta = 50^\circ$ (FEM); (e) maximum shear strain distribution at $\beta = 50^\circ$ (FEM); and (f) maximum shear strain-rate distribution at $\beta = 50^\circ$ (FDM).
out the pseudo-static seismic stability analysis (Melo and Sharma 2004; Perlea and Beaty 2010). The present study performs the pseudo-static analysis for all 33 different locations using FEM at two different slope angles ($\beta$), i.e., 40° and 50°.

5.3. Slope angle optimization

Slope optimization is a technique through which one can have an idea of FOS with varying slope angles ($\beta$). Usually, the slopes with FOS greater than 1 are considered to be stable, however to gain stability in longer term it is desirable to take a FOS at least 1.3 for slopes beside roads and highways (Kainthola et al. 2011). On the other hand, where short term stability is desirable such as in the case of open cast mine, one can work safely with minimum FOS of 1.15 (Bond et al. 2013). Steeper slopes are economical however more prone to slope failure events. Hence, in order to build slopes with minimum cost (steeper slopes) without compromising the safety standard one should perform slope optimization (Chen et al. 2016).

6. Results and discussion

Large scale slope stability assessment using numerical tools coupled with GIS studies descry the ground reality prevalent in the study area. The study marks the slopes with angle 40° to be stable without considering the effect of rainfall and seismic events, as FOS value is greater than 1 except at one location (in FEM) and three locations (in FDM) out of total 33 locations considered in the present work. However, a rainfall of higher intensity or of longer duration will accumulate a significant amount of pore water pressure, reducing the effective shear strength of the slope mass, and consequently, slopes became more prone to failure. The study further investigates the stability scenario of slopes with slope angle 50°, and results of FEM and FDM indicate that 30.30% and 24.24% locations are prone to landslide events, respectively, out of 33 locations involved in the study (Figure 11). At most of the locations the FOS ascertained through finite difference tools are slightly higher than that of finite element techniques, which follows the findings of Ansari et al. (2021).

Moreover, the present work also incorporates the seismic events and their role in slope instability. The pseudo-static seismic slope stability assessment was incorporated using finite element approach.

For the present work horizontal-seismic coefficient ($K_{H}$) value 0.15 is chosen, while keeping the vertical-seismic coefficient ($K_{V}$) value equal to 0. On application of pseudo-static seismic analysis in the study area, the chances of slope failure increase from 30.30% to 36.36% in the case of slope angle ($\beta$)=40°, whereas it rises from 30.30% to 69.69% in the case of slope angle ($\beta$)=50° (Figure 12). The coefficient of correlation between the FOS and FOS with the inclusion of seismic coefficients was quite high. The results are quite practical and easy to implement and should be considered before installation of major infrastructure projects in the study area.

To develop a deeper understanding about stability scenario of the study area, the slope angle optimization was involved in the present work. In the present work, slope optimization for seven different locations were assessed using FDM and the slope
Figure 11. Range of FOS attained for slope angle 40° and 50°.

Figure 12. Correlation of FOS obtained before and after application of pseudo-static approach using FEM.
angle for a FOS would be 1.3 was identified (Figure 13). A steep and regular rise in the FOS values was observed with the corresponding reduction in slope angles. However, for the slope m30, the changes in FOS are a little erratic, which may be attributed to the peculiar material properties for the slope.

It allows the present study to represent FOS as a function of slope angle and empowers the geo-engineers and researchers to design an economical slope with maximum possible slope angle (without compromising the safety standards). The type of infrastructure project being planned in the valley will decide what safety factor it requires.

7. Conclusion

The present study is first of its kind for the Lower Tons valley which entailed a large amount of geotechnical testing and numerical simulation. A total of 80 samples for Atterberg limits and grain size analysis were conducted. Out of the 80, 33 soil samples were further tested for geotechnical parameters. The soils in the study area are coarse in nature, poorly sorted with low plasticity. These soils hold the potential for improvement through compaction. The samples were geotechnically tested in their natural state and the cohesion lies between 7.84 kPa and 94.14 kPa, and friction angles ranged between 24.8° and 60.5°. Eventually, finite element and finite difference techniques were applied on the generalized slopes height of 50 m with two different sets of slope angles (40° and 50°) for 33 locations. For the slopes with slope angle 40°, the finite element approach yields the mean and median FOS values as 1.40 and 1.38,
respectively; whereas, finite difference marks 1.44 and 1.40 as mean and median FOS values respectively. While, the mean and median FOS values for the slope angle 50° are 1.11 and 1.08, respectively (using FEM), and 1.15 and 1.11, respectively (using FDM). Moreover, the slope angle optimization investigation for seven different locations shows that slopes with slope angle equal to 40° or less than 40° are salubrious and economical for large scale infrastructure projects. However, the optimization has not considered the effect of rainfall or earthquake events. Furthermore, pseudo-static seismic approach sheds light on the effect of earthquakes occurring in the study area and finds that the chances of slope failure events increased significantly. The findings on slope optimizations can be used by the local administrators and engineers to demarcate and design stable cut slopes which may require lesser reinforcement.

Data availability
Since the study area from a critical strategic location, the authors are bound to not share the data from the present research work.

Acknowledgment
V.S. would like to express his gratitude to University Grants Commission, India, for the post-doctoral fellowship grant (F./PDFSS-2013-14-UTT-5536) and to Prof. A.K. Blyani for his guidance. A.K. would like to thank Prof. B.P. Singh (HOD), Department of Geology, BHU for all the motivation and support. Rocscience Inc., Itasca Consulting Group Inc., and the R-Project are duly acknowledged for the computational tools.

Disclosure statement
No potential conflict of interest was reported by the author(s).

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