Original Research Paper

# Estimate of Safe Angle for Cut Slopes Under Different Geology and Rainfall Intensity in Central Nepal

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**Abstract:** This research has been carried out on a cut slope of Kathmandu-Terai Fast Track Road near Koppugaon located at Dakshinkali Municipality, Kathmandu. The cutting of the slope without considering the possible effects of geological parameters of slope material may cause unexpected slope failures which may cause loss of lives and properties. This research deals with the effects of rainfall and groundwater conditions on the stability of the cut slope. The cut slope made up of fluvial-lacustrine gravelly soil deposits of Lesser Himalaya is modeled as a finite slope using Limit Equilibrium and Finite Element analysis. The global stability analysis of the slope has been carried out by using Slope/W software, whereas the effects of rainfall (i.e. the fluctuation of groundwater, moisture content, saturated water content, volumetric water content, changes in pore water pressure, and hydraulic conductivity) are analyzed by using Seep/W Software. The slope stability analysis of the cut slope has been carried out without and with the consideration of the effects of rainfall for different angles of inclination of the slope and the safe angle for an FOS >=1.5 for the slope is calculated. The result of the stability analysis of the slope shows that the safe cut slope angle for the slope under consideration is about 48 degrees in dry conditions and 42 degrees in wet conditions which will result in a factor of safety of more than 1.5.

**Keywords:** Slope Stability, Factor of Safety, FEM, LEM, Inclination Angle

## Introduction

Nepal has geographically complex landforms, geologically young and active mountains and it is situated in the seismically active zone. Different types of geological hazards occur in various parts of Nepal among them most prominent hazards are landslides and floods. The stability of the slopes is determined by the geologic material, geomorphology of the area, and other external factors such as human activities on the slope, rainfall events, and groundwater conditions. These factors can be categorized into two sets: Intrinsic and extrinsic factors. The geologic materials, groundwater conditions, and geomorphic features are intrinsic factors while rainfall intensity and frequency, human activities, and seismic activities are the extrinsic factors.

Shen *et al.* (2016) examine how rainfall intensity and slope gradient affect rill erosion processes on hill slopes, as well as the hydraulic characteristics and dynamic mechanisms of rill flow. Bhandari *et al.* (2023) conducted a landslide susceptibility mapping study in the Lesser Himalaya of West Central Nepal, focusing on Baglung Municipality. The study employed various causative factors, including elevation, slope, curvature, land use, geology, rainfall, soil types, soil thickness, topographic wetness index, and stream density, to generate thematic layers. The layers were combined to create a landslide susceptibility map using ArcGIS 10.4.1. Slope failures are common hydro-geotechnical issues in mountainous areas within tropical and subtropical regions worldwide. Three main types of external factors that trigger shallow landslides include geological conditions, hydrogeological influences, and human activities (Acharya *et al.*, 2016).

The Kathmandu Valley experiences various ground stability challenges. Remote sensing data (DInSAR) has revealed several instances of ground subsidence within the valley (Bhattarai *et al.*, 2017). Furthermore, the region is highly vulnerable to landslides, particularly during the monsoon season.

The stability analysis of the slope is carried out using numerous methods depending on the nature of the slope and the purpose of the study. Limit Equilibrium Method (LEM), Numerical Methods (Continuum Modelling, Discontinuum Modelling, and Hybrid/Coupled modeling), Stereographic and Kinematic Analysis, and Limit Analysis (Using software like OptumG2 (2014), Limit State GEO (2018). The most frequently used methods in continuum modeling are the Finite Element Method (FEM) and the Finite Difference Method (FDM), while the most commonly employed methods in Discontinuum Modeling of Numerical Methods are the Discrete Element Method (DEM) and the Discontinuous Deformation Analysis (DDA). The Limit Equilibrium Method (LEM) is widely used for stability analysis and assumes the slope is composed of thin slices.

Slope stability analysis can be performed using traditional approaches such as the Limit Equilibrium Method (LEM), the Finite Element Method (FEM), or the Finite Difference Method (FDM). LEM is typically applied for slopes with simple geometries and fewer parameters, while the other methods are less commonly used in standard design practices.

This research is mainly focused on determining the safe angle of the cut slope in extreme rainfall effects and dry conditions. A comparison is made between stability analysis results obtained for dry conditions and for extreme rainfall effects. The analysis of the slope is carried out considering dry and wet conditions for cut slope angles. The analysis methods used in this research are Morgenstern and Price Methods and Spencer's methods in LEM. The factor of safety obtained from this analysis for dry and rainfall effects are compared. And stability analysis is also carried out in FEM using Plaxis 2D.

## *Study Area*

The study area lies in the Koppugaon of Dakshinkali Municipality in Kathmandu districts of Central Nepal of Province 3 of Nepal (Fig. 1). The area lies at the right bank of the Bagmati River at the southern margin of the Kathmandu valley. Geographically, the study area lies at 27° 35' 35.80" N, 85° 16' 49.26"E to 27° 35'43.64"N, 85° 16' 46.00" E covers the part of the Topo Sheet No. 2785 06C (1:25000 scale) provided by the Department of Survey, Government, Nepal. Geologically the study area lies in the lesser Himalayas of the Nepal Himalayan belt with fluvial-lacustrine gravelly soil deposits and met sandstone and limestone deposits. The study is easily accessible by road and in the section of the road local Bus service is available. Some of the sections where the local road is not available can be accessed with the narrow foot-trail.

## *Geology of the Area*

Kathmandu is a bowl-shaped valley having approx. Diameter ranging from 30 km (EW) to 25 km (NS) nearly circular outline. This basin lies on the bedrock of the Kathmandu Complex, part of the Kathmandu Nappe (Stocklin and Bhattarai, 1981; Sakai, 2001; Rai, 2001). The rock formations of the Kathmandu Complex date back to periods ranging from the Precambrian to the Paleozoic era.

The sources of the basin fill sediments originate from either the metasediments zone in the south, east, or west or from granite gneiss or schist to the north (Sakai, 2001; Paudel, 2014; Paudel and Sakai, 2008). The sedimentary fill in this basin exceeds 500m (Moribayashi and Mauro, 1980; Katel *et al*., 1996). In the upper section of the valley, the sediments are mainly composed of fine sand which comes from fluvial-deltaic environments (Sakai, 2001; Dill *et al*., 2001), in contrast, the southern part features a predominance of diatomaceous earth, pebbly clay, and conglomerate are the predominant materials.

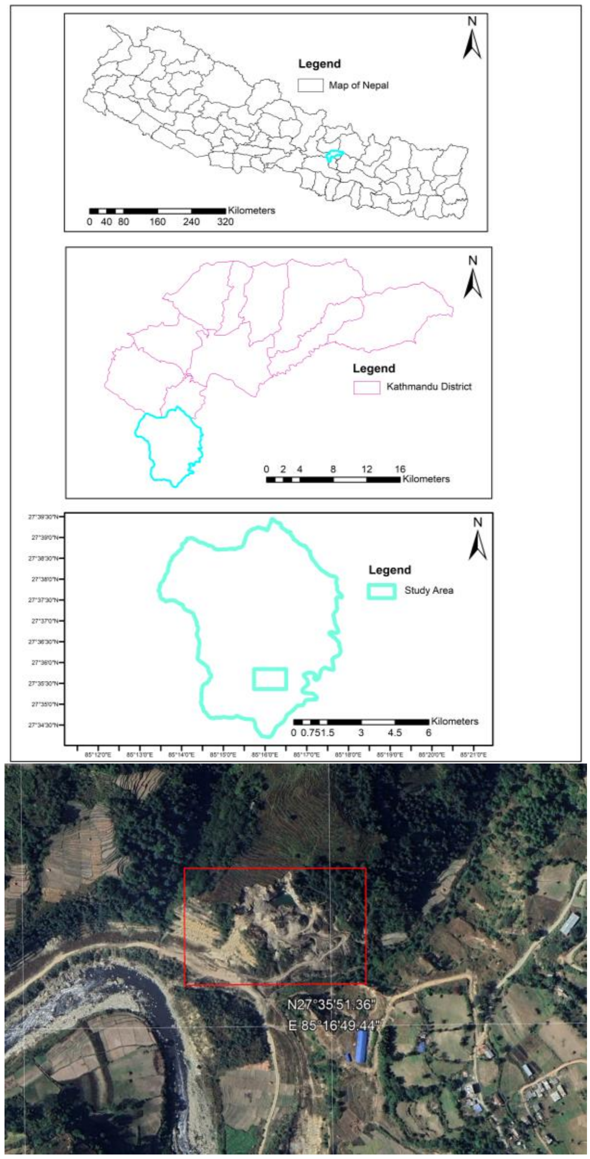


**Fig. 1:** Location map of the study area

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The diatomaceous earth and peat clay are found in many parts but mostly in central and the southern parts of the valley. The sediment facies of the valley are broadly divided into three types: fluvio-deltaic in the north, fluvio-lacustrine in the south to central parts, and alluvial fan and fluvial in the southern margin of the basin. The basin contains deposits of clay, silt, sand, and gravel from the upper Pliocene to the Quaternary period (Moribayashi and Maruo, 1980; Yoshida and Gautam, 1988). These deposits rest on the Precambrian Bhimphedi Group and the lower Paleozoic Phulchauki Group (Stöcklin and Bhattarai, 1981). According to studies by Katel *et al*. (1996); Sakai *et al*. (2002), the basin also holds over 500 meters of sandy and muddy lacustrine sediments.

Kathmandu basin has representative lake sediments of its type, which have drawn the attraction to many researchers from various regions of the world. The researchers (Yoshida and Igarashi, 1984; Dangol, 1985) have investigated the depositional environments and stratification of the Kathmandu Valley Lake sediment. Further research (Katel *et al.,* 1996; Dahal and Aryal, 2002) has focused on the geotechnical characteristics of the sediment in Kathmandu Lake.

In a recent study, Mugnier *et al.* (2011) explored how the Kathmandu Valley Basin responds to seismic activity, revealing that the deformation of soft sediments during earthquakes is primarily influenced by the fluidization of silty layers. These findings, like many others, are based on borehole data collected by different organizations for projects such as water supply and other field studies. However, since the borehole cores were not retrieved, the detailed characteristics and layering of the sediments could not be fully confirmed (Sakai, 2001).

Moreover, Sakai (2001) has mentioned that these previous studies conducted by many researchers faced several important problems in the stratigraphic division and nomenclature of the formations, mainly because of inadequate information on the subsurface geology and insufficient description of the definition of each formation. To address this, Sakai *et al.* (2002) conducted a palaeoclimatic study based on core drilling of the basin-fill sediments in the Kathmandu Basin. This was the first large-scale drilling project within the Kathmandu Valley with full core recovery. However, a detailed examination of the rivers and streams reveals a rectangular drainage pattern (Yonechi, 1973).

Hagen (1969) suggested that the Bagmati River couldn't keep pace with the uplift of the Mahabharat Range, which likely led to a lake forming in the early Pleistocene. Yonechi (1973) identified distinct surface levels in the Kathmandu Valley Basin: The Kirtipur Surface, Patan I Surface, Patan II Surface, Kathmandu I Surface, and Kathmandu II Surface, in descending order. Moribayashi and Maruo (1980) used gravimetric surveys to find that the sediment depth in the Baneshwor area reaches about 650 meters. Dhoundial (1966) categorized the sediments into different groups: A thick sequence of boulders and pebbles named Basal boulder beds located only at the southern margin of the basin, Lukundol formation (consisting of lignite, silt, soft carbonaceous clay, and sand), Kalimati formation (comprising carbonaceous clay, sand, and silt), Sankhu Formation (made up of pebbly sand, silt and clay) and Chapagaon Formation (containing pebbles, granules, sand and silt). Yoshida and Igarashi (1984) carried out comprehensive mapping, pollen analysis, and paleomagnetism of the basin sediments. Based on these studies, the sediments have been divided into eight stratigraphic units: (1) Lukundol formation (2) Pyanggaon terrace deposit (3) Chapagaon terrace deposit (4) Boregaon terrace deposits (5) Gokarna formation (6) Thimi formation (7) Patan formation and (8) Lower Terrace deposits.

The Itaiti formation was named for the three terrace deposits mentioned above, which also separated the sediments into Bagmati and Kalimati formations with the Patan formation and Basal lignite member at the center of Kathmandu Valley and the Terebhir, Itaiti, and Lukundol formation in the south. In the Lukundol formation, weakly cemented sand, silt, and clay with lignite intercalation are found. The Phulchauki and Bhimphedi Group rocks constitute the unconformable base of the Lukundol formation in the southern region of Kathmandu (Dangol, 1985). A variety of stratigraphic units, including talus deposits, terrace gravel deposits, Sunakothi formations, Kalimati formations, Itaiti formations, Lukundol formations, Tarebhir formations, and basement rock, have been identified in the sediments.

The geological cross-section from south to north indicates the thickness of the different stratigraphic units and the variation in the stratigraphic units on moving from south to north. The area marked with the circle pointed by the arrowhead indicates the study area of the thesis work, it lies on the Terrace Gravel Deposit which stratigraphic unit named by (Paudel and Sakai, 2008).

## Materials and Methods

The spots of sample collection, the geometry of the slope, and different layers in the slope are shown in Fig. (2). For these tests, both disturbed and undisturbed (Block sampling) samples were carefully taken using a hand auger, shovel, trowels, and knives depending upon the test requirements. Six samples: PS1, PS2, PS3, PS4, PS5, and PS6 were carefully collected from distinct layers of the slope to undergo detailed laboratory testing.

**Table 1:** Geotechnical properties of soil

| Sample no. | Moisture content (w %) | Sp. gravity | Bulk unit wt. (kN/m$^3$) | Permeability (m/s) *10$^{-6}$ | LL% | PL% | Cohesion (kPa) | Friction angle (°) |
|---|---|---|---|---|---|---|---|---|
| PS1 | 29.71 | 2.58 | 15.85 | 1.28 | 29.66 | 21.60 | 12.33 | 33.63 |
| PS2 | 13.54 | 2.63 | 15.55 | 1.02 | 26.58 | 20.13 | 10.44 | 36.21 |
| PS3 | 4.47 | 2.50 | 14.94 | 1.76 | - | - | 2.62 | 42.10 |
| PS4 | 14.31 | 2.63 | 16.46 | 1.28 | 36.12 | 24.56 | 10.44 | 36.32 |
| PS5 | 5.58 | 1.92 | 15.24 | 5 | - | - | 14.96 | 35.50 |
| PS6 | 29.71 | 2.58 | 15.85 | 1.28 | 47.50 | 26.59 | 12.33 | 33.63 |

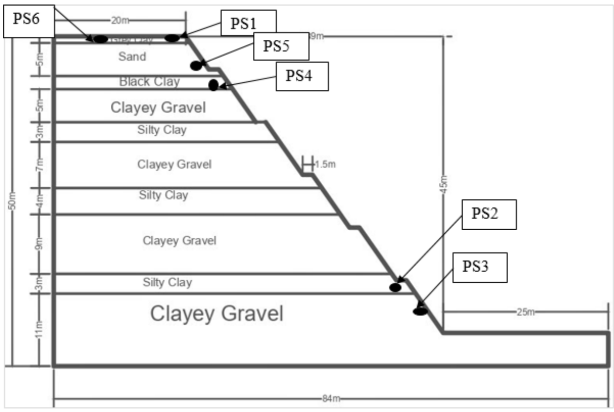


**Fig. 2:** Geometry of the cut slope showing soil layers thickness and width of benches of slope and location of sample collection

The purpose of this testing is to determine the geotechnical parameters: Cohesion (c) and internal angle of friction (ϕ), unit weight (ϒ), Atterberg's limit (LL and PL), and moisture content (w %) and permeability for each layer. These parameters are critical for understanding the stability. Both field studies and the laboratory test results of different geotechnical parameters shown in Table (1) are entered into the prepared slope model in two different software.

The software used for the data analysis are, PLAXIS and GeoStudio (SEEP/W, SLOPE/W). In addition, for drawing the model and map ArcGIS, AutoCAD, and Coral Draw are also used. The rainfall effect is also considered for the second case analysis, for which average rainfall intensity is considered. The seismic consideration is not taken throughout the modeling. The average intensity of the nearby rainfall stations, strength parameters, geometry of slope, and water table are taken as boundary conditions. The stability analysis of the slope is done in SLOPE/W software. In SLOPE/W, the stability

The analysis is carried out using the Morgenstern-Price method and Spencer's method. The Morgenstern and Price (1965) is a method most widely used method in the present days, a basic principle of this method is similar to the other slices method but it allows users to specify interslice force functions. While other simpler methods of analysis do not include all interstices.

## Results

### *Stability Analysis Using LEM*

Using the parameters of slope materials collected from field and laboratory tests, steady-state analysis was carried out using SEEP/W to determine the groundwater conditions necessary for the stability analysis of the slope. The analysis also included rainfall data (Tables 2- 4) from the Chapagaon, Lele, and Khokana rainfall stations, considering the maximum recorded rainfall for the analysis.

The maximum average yearly rainfall and average rainfall data for the monsoon season (June, July, August, and September) were used in the analysis. Slope stability analyses were carried out in SLOPE/W considering two different cases: (i) Dry condition and (ii) Maximum rainfall condition. The stability analysis of the slope was conducted for different slope angles varying from 35-65 degrees. Altogether, five different slope materials: Black clay (CL), silty clay (CL-ML), grey clay (CL), sand (SW), and clayey gravel (GC) were used in the slope model. Average rainfall of $1.59333\times10^{-8}$ m/sec was assumed in the analysis.

**Table 2:** Rainfall Intensity of Chapagaon rainfall station (2002 AD)

| | Rainfall (mm) | Rainfall intensity (m/sec) | Rainfall intensity (m/sec) |
|---|---|---|---|
| Jun. | 189.8 | 1.83*10$^{-8}$ | 1.83E-08 |
| Jul. | 500.7 | | |
| Aug. | 312.1 | | |
| Sep. | 396.6 | | |

**Table 3:** Rainfall intensity of Khokana rainfall station (2002 AD)

| Month | Rainfall (mm) | Rainfall intensity ( m/sec) | Rainfall intensity (m/sec) |
|---|---|---|---|
| Jun. | 131.5 | 1.27* 10$^{-8}$ | 1.27E-08 |
| Jul. | 615.1 | | |
| Aug. | 389.5 | | |
| Sep. | 217.8 | | |

**Table 4:** Rainfall Intensity of Lele rainfall station (2002 AD)

| Month | Rainfall (mm) | Rainfall intensity (m/sec) |
|---|---|---|
| Jun. | 173.7 | $1.68*10^{-8}$ |
| Jul. | 843.2 | |
| Aug. | 473.5 | |
| Sep. | 388.4 | |

### *Slope Model*

The existing cut slope has a height of 50 meters, with the lowest point at an elevation of 1260 meters and the top at 1310 meters. For the continuous slope, the water table is estimated to be 5 meters below the surface at the top and 6 meters below at the bottom, based on observations from nearby ponds and tube wells. This estimation is used for the slope stability analysis.

The material properties of the cut slope are assigned in SEEP/W. Each layer of the slope is individually characterized with the necessary parameters for the analysis, including the assumed groundwater table. SEEP/W analysis is then conducted to determine the pore water conditions of the slope. The results from the SEEP/W analysis are used as the basis for the SLOPE/W analysis.

This procedure is repeated for saturated conditions under maximum rainfall. Properties such as soil permeability, saturated water content, and rainfall intensity are assigned to the respective soil layers. The factor of safety obtained from different scenarios is compared and the results are interpreted accordingly.

### *Stability Analysis of the Existing Slope Using LEM*

The existing cut slope has an average angle of 62°, featuring six benches, each with an average height of 8 meters and a width of 1.5 meters. The slope is composed of six different types of soils: Black clay, silty clay, and clayey gravel. The cohesion of the slope materials ranges from a minimum of 2 kPa to a maximum of 14.96 kPa. The internal friction angle of the slope materials varies from 33-42°. The plasticity chart for the fine slope materials indicates that the soil has low to medium plasticity. The unit weight of the soils ranges from 15-19 kN/m³. Stability analysis was performed using these soil parameters with Geo Studio 2012 software.

The existing slope appears theoretically stable under dry conditions, with a factor of safety ranging from 1.155-1.066 using the Morgenstern-Price method and Spencer's method. Generally, a slope having a factor of safety value one or greater is considered indicative of a stable slope. However, in practice, when the factor of safety is 1.5 or greater. The calculated factor of safety under current conditions suggests that the slope is theoretically stable, but in real ground conditions, there can be many cracks on the crown part of the slope indicating a higher possibility of slope failure with nearly equal results from Morgenstern-Price and Spencer's methods.

When analyzing the slope stability with rainfall data, the results indicate that the existing slope remains stable, with a factor of safety of 1.004 using the Morgenstern-Price method and 1.0001 using Spencer's method. The similarity in results from both methods confirms the reliability of the stability analysis under the given conditions.

### *Stability Analysis of Slope at Dry Condition*

The stability analysis was conducted for this case, neglecting groundwater conditions and rainfall effects. The stability analysis in dry conditions was carried out for different cut slope angles. The cut slope fails at an angle of 68°, as indicated by the analysis. The results show that the maximum cut slope angle for this slope is about 68°; beyond this angle, the slope will not be stable.

For a stable cut slope design under dry conditions, a similar analysis was performed using different slope angles until the factor of safety equaled 1.5. The results from the analysis show that the slope will be stable at 48° with a factor of safety of 1.5. Thus, the safe angle for the given slope in dry conditions is approximately 48°.

The factor of safety of the slope at 67° from both Spencer's and Morgenstern Price's method indicates that the slope is not stable for an angle greater than this in dry conditions. Figures (3-4) demonstrate the value of the factor of safety from Spencer's and Morgenstern's Price method, 0.994-1.006 respectively. Similarly, at 65°, the values are 1.00 (Fig. 5) and 1.048 (Fig. 6) respectively.

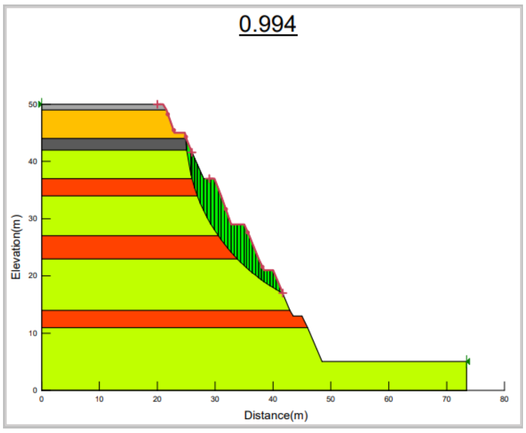


**Fig. 3:** Stability analysis using Spencer's method at dry condition for 67° and factor of safety obtained is 0.994

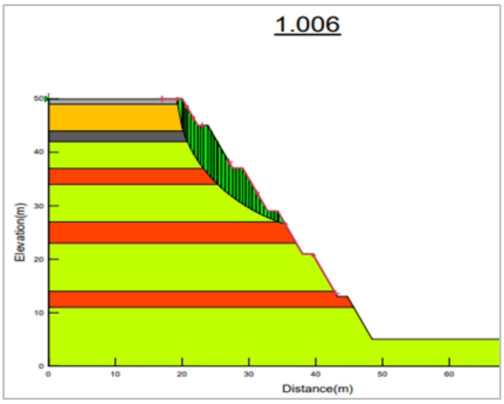


**Fig. 4:** Stability analysis using Morgenstern and Price method at dry condition for 67° and factor of safety obtained is 1.006

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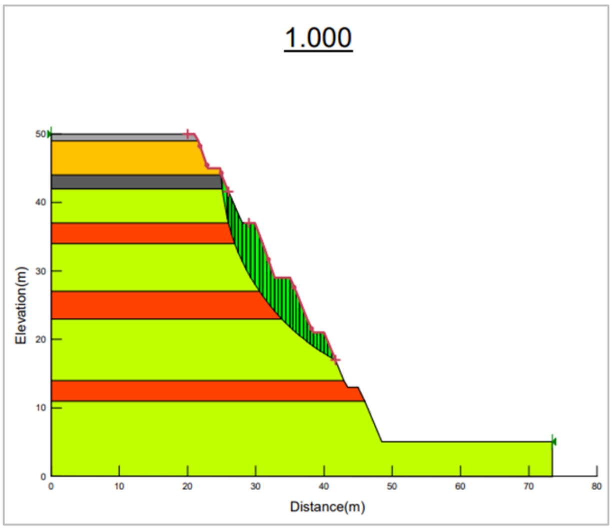


**Fig. 5:** Stability analysis using Spencer's method at dry condition for 65° and factor of safety obtained is 1.00

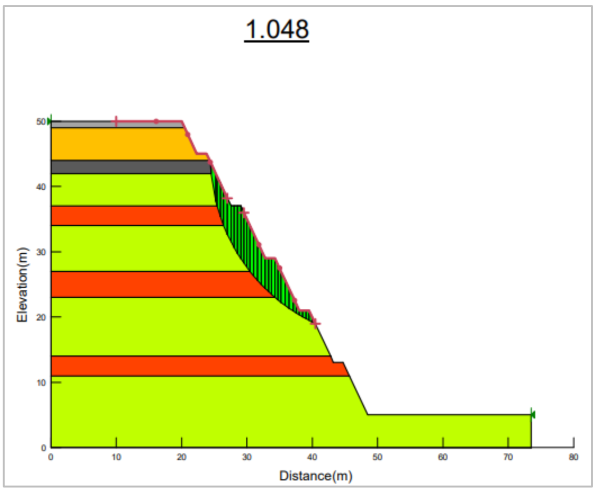


**Fig. 6:** Stability analysis using Morgenstern and Price method at the dry condition for 65° and factor of safety obtained is 1.048

*Stability Analysis of the Slope with Consideration of Rainfall*

For the stability analysis of the slope with rainfall data, rainfall data from the Chapagaon rainfall station of the year 1985 is considered. The groundwater table for the cut slope is assumed at 30 m below the top of the cut slope. The seepage line of the slope is also considered in the stability analysis. The SEEP/W analysis is used to calculate the pore water pressure condition, which is then modeled in the SLOPE/W. The result obtained from SEEP/W is then used as parent analysis for the stability analysis to calculate the factor of safety. The SLOPE/W analysis is held using the Morgenstern and Price method. The result of the analysis shows that the pore water pressure has a significant effect on the stability of the slope. This effect will be more significant at the lower portion of the slope and it will decrease continuously towards the upper portion of the slope as indicated in Fig. (7).

The analysis results show that the slope with rainfall effects fails at 64° and the factor of safety obtained from the Morgenstern and Price method is 0.994. The red color zone in Figs. (7 and 10) indicates the zone with a higher head at the uppermost part of the slope. At that part of the slope, the total head is greater than 45 m. But pore water pressure is maximum in the lower part of the slope. Figures (8-9) show the value of the factor of safety at 60° of slope angle for both of the methods. Similarly, Figs. (11-12) shows the value at 45° with rainfall effect. The results show that it is continuously increasing with a decrease in slope angle for the same condition of the rainfall intensity.

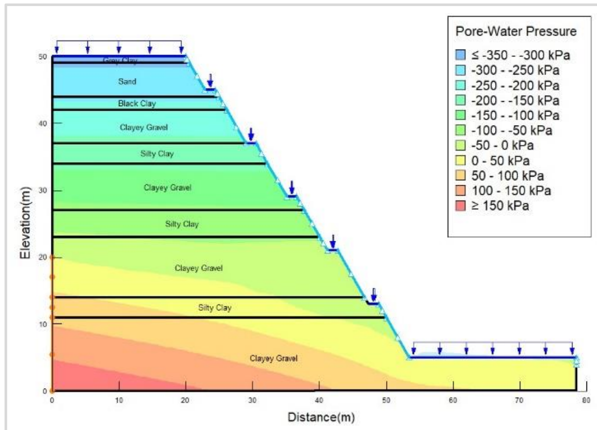


**Fig. 7:** Pore water pressure condition obtained from SEEP/W analysis at 60° with rainfall data

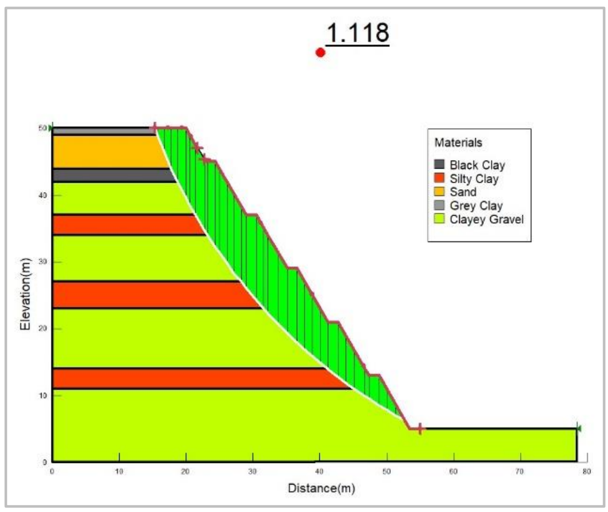


**Fig. 8:** Stability analysis using Morgenstern and Price method with rainfall effect at 60° and the factor of safety obtained is 1.118

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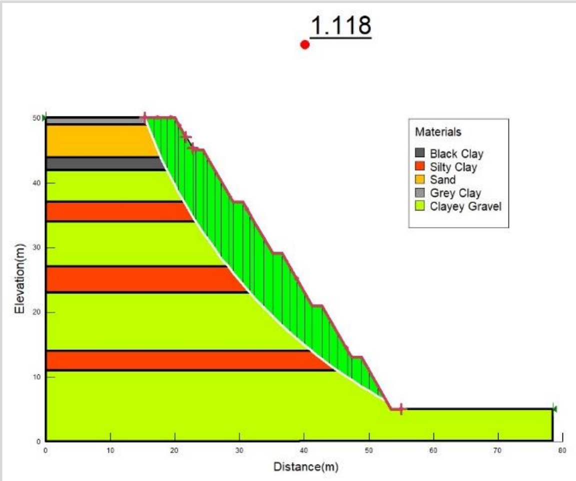


**Fig. 9:** Stability analysis using Spencer's method with rainfall effect at 60° and the factor of safety obtained is 1.118

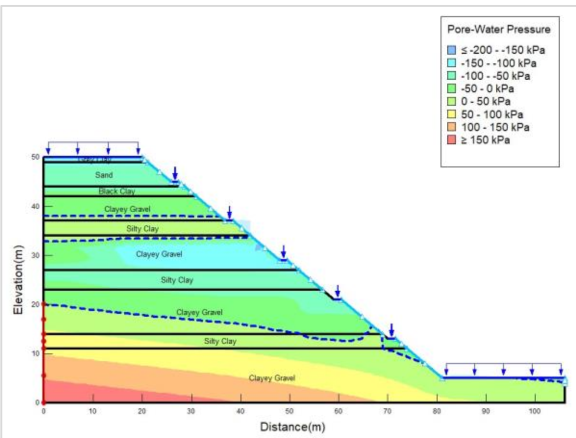


**Fig. 10:** Pore water pressure condition obtained from SEEP/W analysis at 42° with rainfall data

Figure (9) shows the pore water pressure condition of slope at 42° of slope angle obtained from the SEEP/W analysis. The pore water pressure condition is maximum to the lower part of the slope. Figures (10-11) show the analysis results obtained at 42° for both methods, the factor of safety from both methods is nearly the same and the obtained values of the factor of safety are 1.508-1.507 respectively.

The analysis of the slope with rainfall effects was carried out for different cut slope angles. The result shows that the slope starts failing at an angle of 64°. A slope angle greater than 64° will not be stable during rainfall.

To find a safe angle for the given slope considering the effects of rainfall, the analysis is repeated for different slope angles until the safe angle is found. The results show that with the effects of rainfall, the safe angle will be about 42°, which will result in a factor of safety of 1.508. The threshold angle for the safe design of slope by considering the extreme rainfall events, the slope should be trimmed at an angle of 42° or less.

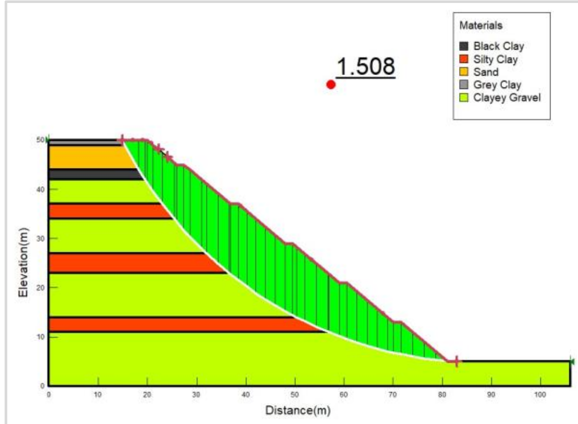


**Fig. 11:** Stability analysis using Morgenstern and Price method with rainfall effect at 45° and the factor of safety obtained is 1.508

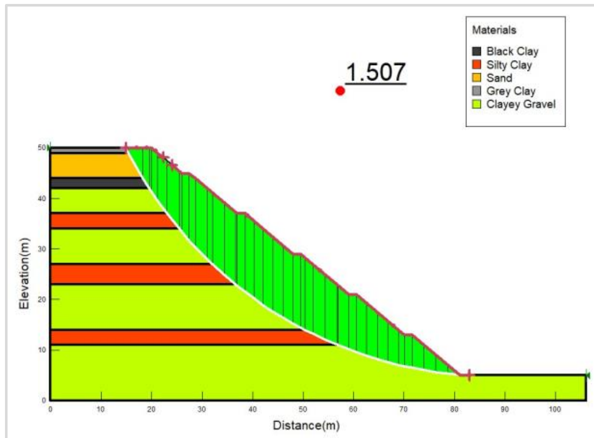


**Fig. 12:** Stability analysis using Spencer's method with rainfall effect at 45° and the factor of safety obtained is 1.507

### *Comparison of the Slope Stability Analysis Results*

The slope analysis was carried out in two different conditions of the slope, the first condition of the analysis was carried out in the dry condition of the slope, in this case, analysis of the groundwater table and the rainfall is not taken into consideration. The Result obtained from the stability analysis (Morgenstern and Price Method) from SLOPE/W analysis shows that the factor of safety of the existing cut slope is 1.115 during the dry condition and 0.995 during the wet condition of the slope.

The analysis was done for different slope angles and the factor of safety value for the dry and rainfall conditions was calculated. The comparison was made for the obtained values of these two different cases as shown in Fig. (13). At first, the stability condition of the existing slope was carried out under dry conditions. The existing slope is found to be stable with a factor of safety of 1.115. The existing slope is at an average angle of 62°, then, further analysis of the slope is carried out for different slope angles.

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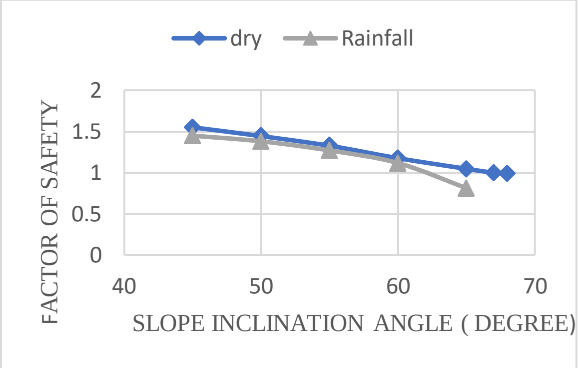


**Fig. 13:** Comparison of a factor of safety versus slope angles at two different conditions, dry and rainfall effect

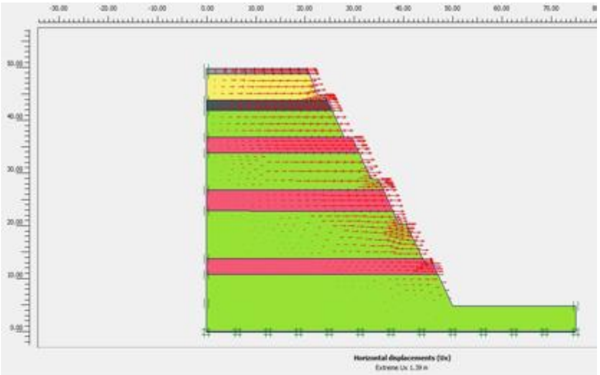

**Fig. 14:** Showing horizontal displacement arrows of existing slope at 62°

The cut slope will fail at 68° (even in dry conditions). For a safe design of slope, it should have a factor of safety of 1.5 or more. If we design this slope for completely dry conditions, the cut slope angle should be 48° or less. Therefore, the threshold angle for the safe design of the slope in completely dry conditions is 48°.

In the second case, the stability analysis of the slope is carried out considering the effect of the rainfall. A rainfall of $1.59333*10^{-8}$ m/sec was used for the analysis and the analysis was carried out in SEEP/W, the pore water pressure is simulated in SEEP/W analysis by steady-state analysis, and the analysis is used as the parent analysis for the SLOPE/W. Morgenstern Price and Spencer's Method were used to calculate the factor of safety.

The analysis shows that the factor of safety will significantly decrease due to the fluctuation in the groundwater table and increased pore water pressure in the slope. The stability analysis with the rainfall effects shows that the existing slope is found to be stable at 1.004. The slope will fail at an angle of 64°. This clearly indicates a significant decrease in the factor of safety values with rainfall effects.

The analysis of the slope with rainfall is repeated for the different slope angles. From this analysis, the threshold angle for the safe design of the slope is found to be 42°. The slope should be trimmed or modified with the angle of slope < or = 42° so that it will have a sufficient factor of safety of 1.5.

### *Slope Stability Analysis Using FEM*

Finite element analysis is conducted using the Mohr coulomb model in PLAXIS 2D. Medium-sized mesh is used and the analysis was carried out for a 62-degree slope angle a comparison was made with the LEM results, a slight change in the factor safety value in FEM, the factor of safety is quite higher than that obtained from LEM analysis. The figure shows the factors of safety and displacement plots. The factor of safety value in LEM analysis is 1.155 while the value obtained from FEM analysis is 1.025 which is nearly equal. Similarly, for the slope angle of 48°, the calculated factor of safety from LEM is 1.500 while from the FEM is found to be 1.49. The result from both of the analyses is nearly the same.

Figure (14) shows the horizontal displacement vectors for the existing slope. The arrows directed outwards from the slope indicate the direction of the slope movements. Similarly, Fig. (15) shows the horizontal displacement shading. The different color shading represents the amount of displacement vectors, red color shading has maximum displacement while blue color shading has minimum displacement. The shallower part of the slope has greater displacement than the deeper part of the slope, so the shallower part is more likely to occur failures. Also, the deeper the slip surface of the slope, the more the value of the factor of safety, and hence more stable will be the slope.

The factor of safety versus displacement vector indicates that the slope is displaced by 17 cm with a factor of safety of 1.05. The slope has a high value of displacement which is sufficient for the occurrence of failure. Therefore, the slope is susceptible to failure as represented by the displacement. The red color shading has displacement while the blue has the lowest value of displacement vector. The total displacement shading also represents the shallower portion of the slope is more susceptible to failure than the deeper portion of the slope. Figure (16) shows the plot of a factor of safety versus displacement at a slope angle of 48°.

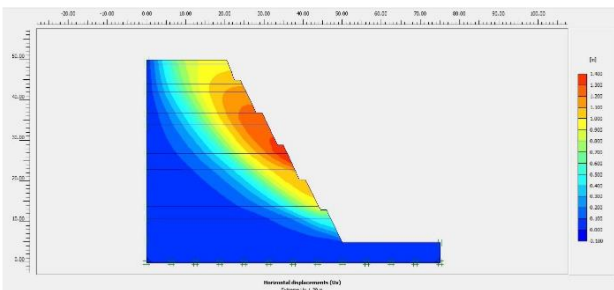

**Fig. 15:** Horizontal displacement contours, representing low displacement with blue to maximum displacement with red color region

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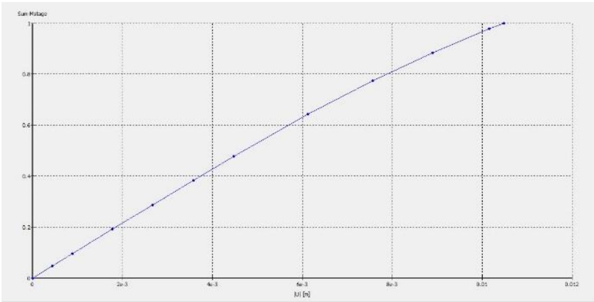


**Fig. 16:** Factor of safety versus displacement for slope angle of 48°

## Discussion

The slope is composed of medium stiff and dense fine and coarse materials. The coarse material of different sizes is dominant with the many small bands of fine materials such as silt, clay, and sand. The top part of the slope contains many thin bands of clay, silts, and sand. The area lies in the Terrace Gravel Deposits, formation is mostly dominated by gravel deposits with bands of black clay, silts, and sand, Paudel and Sakai (2008). Both the fining and the coarsening upward sequence can be observed. Fine soil has low to medium plasticity as indicated by the plastic limit and the liquid limit of the soil. The plasticity Index of the fine soil ranges from 6.45 to 20.41 from minimum to maximum comparing the tested samples. The plasticity chart shows the soil is low to medium plastic clay and silts.

The fine-grained soil is classified as CL and CL-ML. For the classification of the coarse soil, the sieve analysis results were used and the results show that the soil is GC and SW. The gradation of the coarse-grained soil is carried out based on the value of Cu and Cc of the soil. The soil is found to be well-graded soil. The moisture content of the soil ranges from 5.58-29.71% for the test samples. The Fine soil material has a greater moisture content in comparison to the coarse soil. The porosity of the soil plays an important role in the variation of the moisture content of the soil and organic material in the soil also controls the moisture content of the soil. The average moisture content of the soil near the study area, Chapagaon area is 35% and the soil is medium to high plastic (Pradhan, 2014). The results are nearly similar to the results obtained in the thesis study area, Koppugaon. The soil has low to medium plastic as indicated by the analysis of the lab tests data.

The unit weight of the slope material ranges from 15-18.9 kN/$m^2$. The black clay has the highest value among the all-test samples and the sand has the lowest value. The unit weight of the soil sample of the Chapagaon area ranges from 15-17.5 kN/$m^2$, (Pradhan, 2014) which value is nearly similar to the thesis study area.

The internal friction angle and cohesion of the slope material vary from 2-14.96 kN/$m^2$ and 33.63-42.10° respectively. The high plastic clay has high values of cohesion and the coarse soil has a high value of the internal friction angle. The value is similar to as indicated by Pradhan (2014).

The pore water pressure due to the groundwater table considered and extreme rainfall events of 1985 recorded by the Chapagaon rainfall Station is not uniformly distributed in all parts of the slope. The pore water pressure in fine slope material seems to be higher in comparison to the pore water pressure in coarser material. The permeability of the fine slope material is less than that of the coarser slope material so the pore water pressure is generated in fine material and creates the higher value of the pore water pressure. The seep/W analysis of the slope was conducted with five different soil types, Black clay, Sand, grey clay, silty clay, and clayey gravel. The pore water pressure is higher in the layer of silty clay at the lower part of the slope and the value decreases moving to the upper part of the slope. The pore water pressure varies from the highest 150 kPa to the lowest -350 kPa at the lower part and upper part of the slope.

The purpose of placing a bench on a slope is to change the behavior of one high slope to several lower ones. Benches should be wide enough for this reason. With a strong slope of contact and collision, the main purpose is to make the slope flat (Abramson *et al*., 2001). Slope shape is also used to control erosion and establish vegetation. Straight bench lengths are approximately 25-30 ft. Each bench must have a drainage system to transfer the flow to a suitable drainage system (Abramson *et al*., 2001).

The calculated aspect of protection has interpreted the usage of a general that, common minimum applicable values of an element of safety within the slope balance evaluation are; 1.3 for the end of creation and multistage loading, 1.5 for every day long-term loading conditions and 1.00–1.2 for fast drawdown (Duncan, 1996).

About 10 days of rainfall of 586 mm leads to a significant decrease in the value of the factor of safety from 1.33 to 1.05. The significant decrease in the value of the factor of safety is due to a reduction in the effective stress by the increased pore water pressure (Oh and Lu, 2015).

The cohesion and internal friction angle of the soil sample are determined by the direct shear test, the disturbed sample in this test may lead to some errors. The accuracy of the tested data can be increased by a triaxial test. The sampling tube was used to determine the field density of the soil sample. The actual compaction of the soil may be different to some extent from the compaction of the tested soil sample. The permeability of the soil sample was used from the standard table value according to the soil types. The layer thickness of the soil was directly measured in the field in the accessible part of the slope, but some parts of the slope were not accessible. In the inaccessible part of the slope, the thickness of the soil layers was measured by approximation which leads to some error in the measurement.

The stability analysis of the slope in two cases, dry conditions, and rainfall effects suggests, that the existing slope is stable in both conditions. The factor of safety for dry conditions is 1.155 by Morgenstern and Price Method and 1.066 by Spencer's Method. In the second case, with the rainfall effects on the slope, both methods, Morgenstern and Price and Spencer's method give nearly the same factor of safety value of 1.002. The slope can be considered stable with the rainfall effects at the existing condition of the slope. The stability analysis results from the FEM show that the existing slope is stable with a factor of safety 1.05 which is nearly similar to the results obtained from the LEM. For the slope at completely dry condition, the slope is stable below 67° of slope angle and fails above that angle. The slope at (> or =) 67° is at the most critical case, the failure of the slope starts above that angle of the slope at a completely dry condition of the slope.

The stability analysis of the slope using Morgenstern's Price method and Spencer's method show that the factor of safety value for the same condition of the slope is nearly similar. The results obtained from both methods show no wide change in results. Only by a small fraction of the factor of safety values varied. Morgenstern's Price method higher value of the factor of safety by a small fraction than Spencer's Method. But significantly changed the results of the stability analysis of the slope.

The stability analysis at different angles of the slope below that critical angle the safe angle of the slope at dry condition is 45° with a factor of safety 1.500. Therefore, the slope should be trimmed below that safe angle for the safe design considerations for a slope structure.

The second case analysis of the slope, with the extreme rainfall effects on a slope. The analysis results show that the existing slope is stable with a factor of safety of 1.004 from both Morgenstern Price and Spencer's methods. The slope failure starts at 64° of slope angle.

The slope above this angle can be considered as the critical. The analysis was repeated for varying slope angles to determine the safe angle of slope with extreme rainfall events, the safe angle is found to be 42°. For the safe design consideration of the slope, the slope angle should be maintained < or = 42°. The factor of safety at 42° is 1.508 by the Morgenstern Price method.

In FEM analysis of the slope for dry condition of slope large displacement in slope about 17cm which may suggest the slope may be susceptible to failure although the factor of safety is greater than 1.00. The value of the factor of safety given by FEM analysis is lower by some fraction than the factor of safety value calculated from LEM analysis. Burman *et al.* (2015) conducted a comparative study on LEM and FEM in solving slope stability problems. The result shows the value of factor of safety from both methods agrees very well in homogeneous soils. On the other hand, Aryal (2006) investigates that FEM may give a 5-14% lower factor of safety than LEM due to better computations of stress redistributions in different geometric and loading conditions. Generally, comparative studies (Burman *et al.*, 2015) show that FEM provides various advantages over LEM in simulating slopes with complicated boundary conditions.

Alfat *et al.* (2019); Navya and Hymavathi (2017) investigate the effect of slope geometry on slope stability. The study indicates that with decreasing slope angle in a single slope profile, a factor of safety gets increased and further improvement of a factor of safety was observed by applying benches. Similarly, Hulagabali *et al.* (2019) confirm that an increase in slope angle and slope height results in a significant reduction of a factor of safety.

## Conclusion

The stability analysis results lead to the following conclusion.

The factor of safety calculated from both FEM and LEM shows that the existing slope is theoretically stable at the present condition and in completely dry conditions it would be about 1.155 from LEM and 1.025 from FEM. Although the value is greater than 1.00 from FEM analysis, displacement is higher which is about 17 cm, the slope may fail at this value of displacement. In real ground conditions, there were many cracks seen on the top part of the slope which indicates the possibility of slope failure.

The factor of safety of cut slope under the influence of rainfall will be 1.002 (from both methods Morgenstern's Price and Spencer's Method).

The safe angle for the cut slope at dry conditions is 48° with a factor of safety of 1.500 and with the rainfall effects the safe angle of the cut slope is 42° with a factor of safety of 1.508.

The simulation of the rainfall in the SEEP/W indicates that the pore water pressure is higher in the fine-grained soil layer, in clay and silt clay in comparison to the coarse soil sand and gravel.

The stability analysis results from both analysis methods LEM and FEM showed that there are no significant changes in the values of the factor of safety and the in LEM analysis also both Morgenstern's Price and Spencer's method shows nearly similar results.

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## Author's Contributions

**Prabin Shrestha:** Report writing, data analysis, and modeling.

**Khomendra Bhandari:** Field visits and report writing.

**Mahendra Acharya:** Data analysis.

**Anil Ghimire:** Field visit and data collection.

**Suraj Belbase and Asim Timalsina:** Field visits, data collection, and data analysis.

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## Ethics

We wish to declare that there are no any conflicts of interests associated to this research publication.

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