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RESEARCH ARTICLE

GEOLOGICAL STUDIES OF THE SISDOLE-BANCHARE DANDA LANDFILL SITES OF THE NUWAKOT DISTRICT, CENTRAL NEPAL

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ABSTRACT

This manuscript investigates the unexplored slope stability of the Sisdole landfill site, emphasizing the critical need for comprehensive assessments during construction and operation to mitigate potential damages to people, property, and the environment. Focusing on the geological characteristics of the Banchare Danda and Sisdole landfill area, which comprises deformed metasandstone and pegmatite dykes, the study reveals the presence of two anticlines, with the proposed Banchare Danda landfill site strategically positioned. Laboratory analyses of waste/soil samples collected from Sisdole determined cohesion, angle of internal friction, and unit weight. Three slope profiles underwent numerical modeling using the Morgenstern-Price method, including constant and probabilistic analyses, revealing a factor of safety below the prescribed threshold. Seismic and dynamic analyses indicate hazardous conditions for slopes exposed to peak ground accelerations exceeding 250 gals, underscoring the urgency for enhanced design considerations and risk mitigation strategies in landfill operations.

KEYWORDS

landfill site, geological studies, stability analysis, numerical modeling, a factor of safety, peak ground acceleration

1. INTRODUCTION

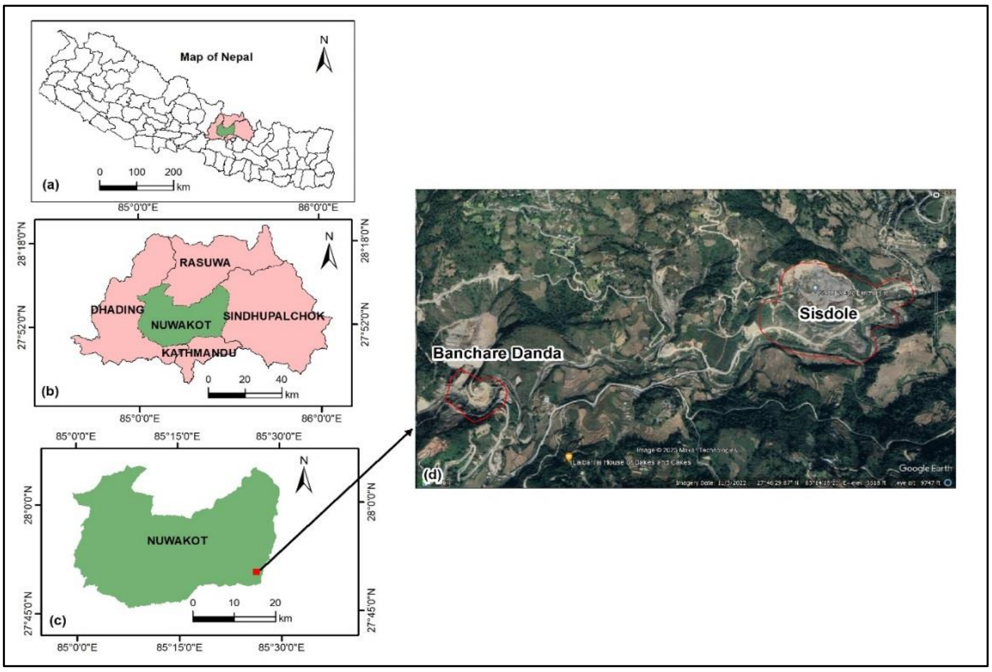

Figure 1: Location map of the study area (1a: Nuwakot districts along with neighboring districts in the map of Nepal, 1b. Nuwakot district with neighboring districts 1c. Nuwakot district 1d. Google image showing the location of the Sisdole and Banchare Danda landfill sites

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Waste, a byproduct of routine human activities, poses significant challenges to both human health and the environment, as highlighted (Dev, 2007). To address this concern, hazardous waste necessitates secure disposal methods, with engineered or sanitary landfills emerging as widely adopted containment systems for Municipal Solid Waste (MSW). The appeal of sanitary landfills lies in their ability to effectively manage a majority of MSW at a comparatively lower cost than alternative methods. Geotechnical considerations, including environmental assessments, play a pivotal role in the design and operation of landfills, with stability emerging as a critical factor. The work of Shafer underscores the importance of a factor of safety greater than 1.5 for stable landfill slopes (Shafer, 2000). Other researchers, such as have delved into various aspects of landfill stability, including the impact of biosolids, slope stability analysis using software like SLOPE/W and GALENA, and the influence of seismic factors (Varjirkar, 2004; Das, 2011; Trivellato, 2014; Yang et al., 2016; Dolp, 2014). However, the specific geological and slope stability analysis of landfill sites in the context of Nepal remains largely unexplored.

This study addresses this gap by focusing on the Sisdole landfill site and the proposed Banchare Danda landfill site in the Nuwakot district of Bagmati Province, Nepal (Figure 1). Situated in the Lesser Himalaya of central Nepal, the Sisdole landfill site, covering an area of 50,000 m^2, is a critical waste disposal facility for the Kathmandu Valley. The geology of the area is complex in the sense of structural complexity (Stöcklin and Bhattarai, 1977). As the valley generates 800 tons of solid waste daily, proper waste management is imperative. The proposed Banchare Danda landfill site, located 3 km west of Sisdole, adds a dimension to waste disposal strategies. Despite the region experiencing stability analyses for rock and soil cut slopes, a comprehensive study addressing geological and slope stability perspectives of landfill sites is notably absent. This study, therefore, aims to fill this void, emphasizing detailed geological assessments and stability evaluations from Sisdole to Banchare Danda, with a primary focus on determining the slope stability conditions of the Sisdole landfill site. The outcomes are expected to contribute significantly to sustainable waste management practices in the region.

2. Methodology

The study was systematically conducted in several key steps to comprehensively assess the geological and slope stability aspects of the Sisdole landfill site. The sequential procedures included (i) a thorough literature review, (ii) a detailed field study, (iii) laboratory investigations, and (iv) subsequent data analysis and interpretation, as illustrated in Figure 2.

2.1 Geological Mapping and Field Study

Topographical maps (Ranipauwa-2785 01 D and Shivapuri-2785 02C) at a scale of 1:25,000 were employed alongside satellite images from Google Earth for the preparation of geological maps and cross-sections. The primary objective of the field study was to gather geological data and collect landfill samples for subsequent laboratory analysis. Geological data, including rock samples, were collected systematically, and twelve soil and waste samples from the Sisdole landfill site were acquired using trench and grab sampling techniques with a cylindrical PVC pipe (Figure 3).

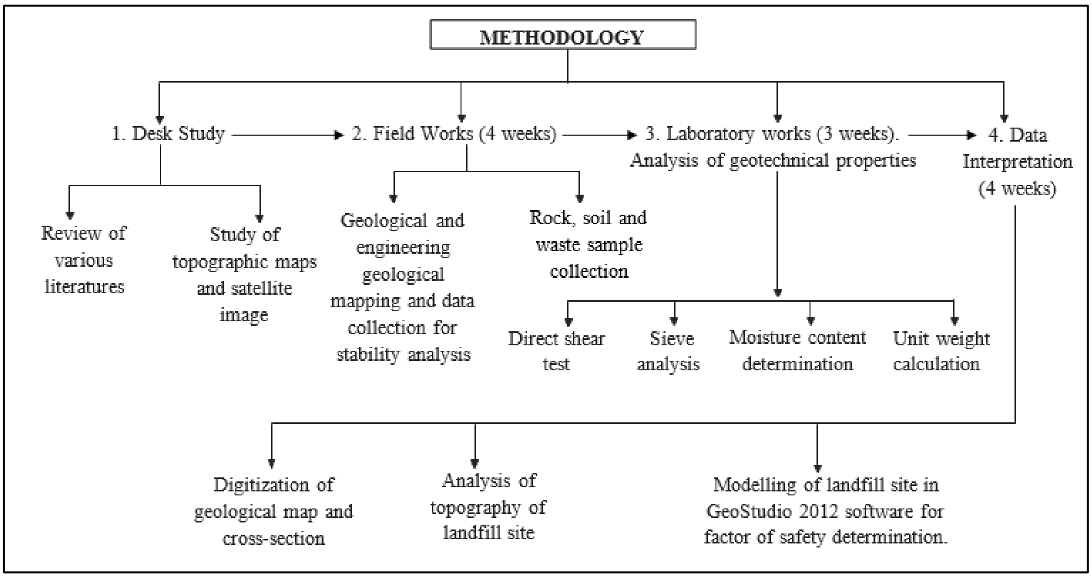

Figure 2: Flow chart showing the methodology adopted

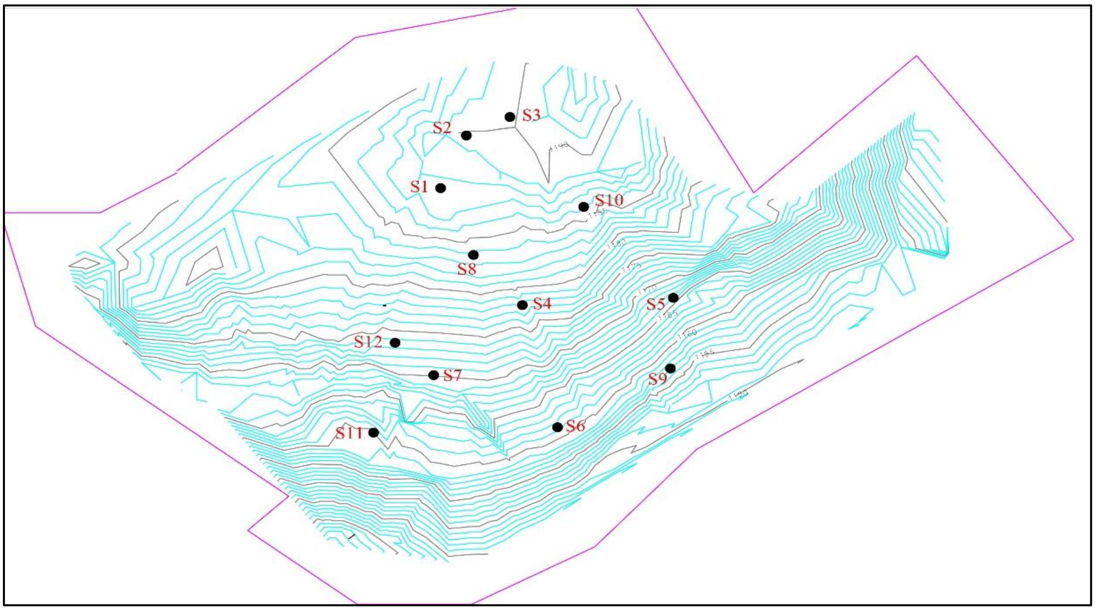

Figure 3: Location of the soil and waste samples taken

2.2 Laboratory Analysis

Upon collection, the acquired samples underwent rigorous laboratory analysis. To prepare the slope profile of the Sisdole landfill site, GPS technology was utilized, and non-biodegradable particles exceeding 19 mm were eliminated. The determination of unit weight was carried out through weight-volume relationships, while shear strength parameters (cohesion and friction angle) were assessed using the direct shear test.

2.3 Slope Stability Analysis

For slope stability analysis, GeoStudio 2012 software, specifically SLOPE/W, was employed. The limit equilibrium analysis considered several factors, including the direction of the slip surface, the selection of analytical methods (Morgenstern-Price and half-sine function), and the division of the waste layer into Upper, Middle, and Bottom regions. The analyses were performed under the circular failure model, with entry and exit methods defining the slip surface. Initially, a deterministic/constant method was utilized for factor of safety distribution calculations and critical factor of safety determination.

2.4 Probabilistic Analysis

Following deterministic analyses, a probabilistic assessment was conducted. Unit weight, cohesion, angle of internal friction, and other parameters underwent normal probability distribution, with Monte Carlo simulation involving a suitable number of trials. The resulting safety factor probability distribution, reliability index, and probability of failure were subsequently computed.

2.5 Seismic Analysis

The seismic analysis, considered the most critical scenario, involved incremental increases in horizontal and vertical seismic coefficients at predefined intervals. The corresponding change in the factor of safety was calculated, with assigned seismic coefficients ranging from 0 to 0.3 for both horizontal and vertical components. This multifaceted methodology integrates field, laboratory, and analytical approaches to comprehensively evaluate the geological conditions and slope stability of the Sisdole landfill site and the Banchare Danda landfill site, offering valuable insights for sustainable waste management practices.

3. Results

3.1 Geology

A generalized columnar section (1:2500) of the rock exposed on the vicinity of the Sisdole-Banchare Danda landfill sites was prepared (Figure 4). Then, the geological map and geological cross-section in a 1:15,000 scale were prepared (Figure 5). The rocks of the region can be classified into two distinct lithological units: the Tistung Formation (south) and the Sheopuri Gneiss (north), described briefly as follows:

3.1.1 Tistung Formation

This unit is mapped as the topmost geological unit of the Bhimphedi Group (Stöcklin and Bhattarai, 1977; Stöcklin, 1980). The Tistung Formation is dominated by metasediments, phyllite, gneiss and pegmatitic dykes. The ratio of meta-sandstone/phyllite is about 3:1 at riverbed of the Kolpu Khola (Figure 6a), and the ratio of metasandstone decreases to the northern mountainous area. A fairly large dyke of pegmatite is found in the northern slope of the landfill site (Figure 6b). The Tistung Formation are deformed, presumably due to the influence of the adjacent gneiss intrusions (Sheopuri Gneiss). In the study area, Kolpu Khola entirely flows through the Tistung Formation.

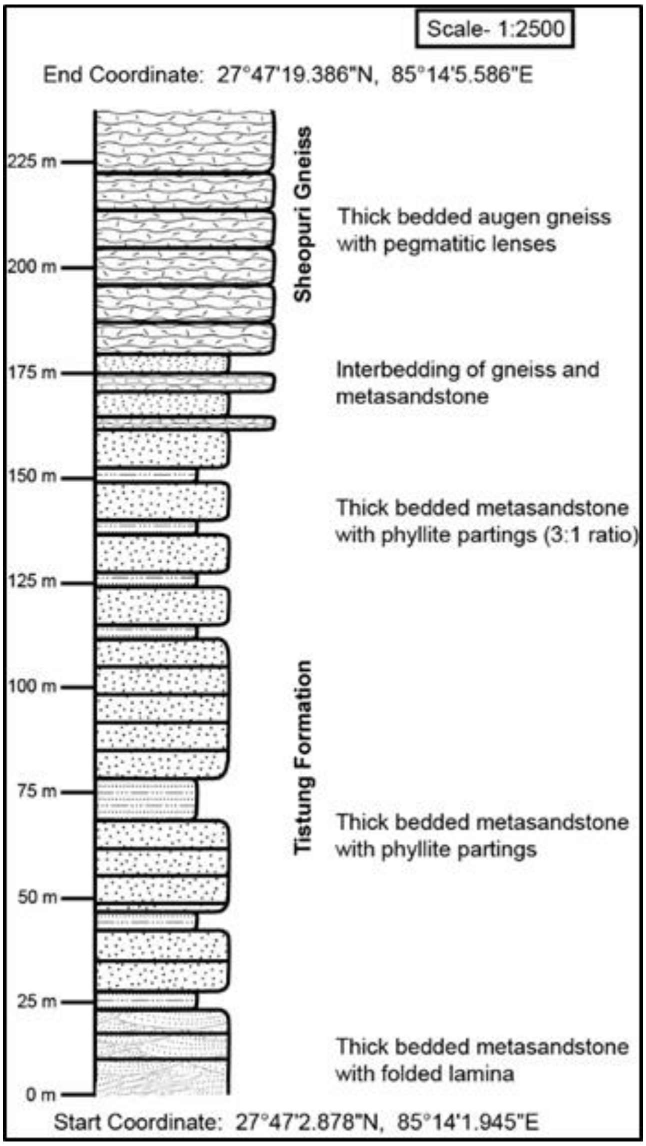

Figure 4: Generalized columnar section of the rocks exposed at Sisdole-Banchare Danda section

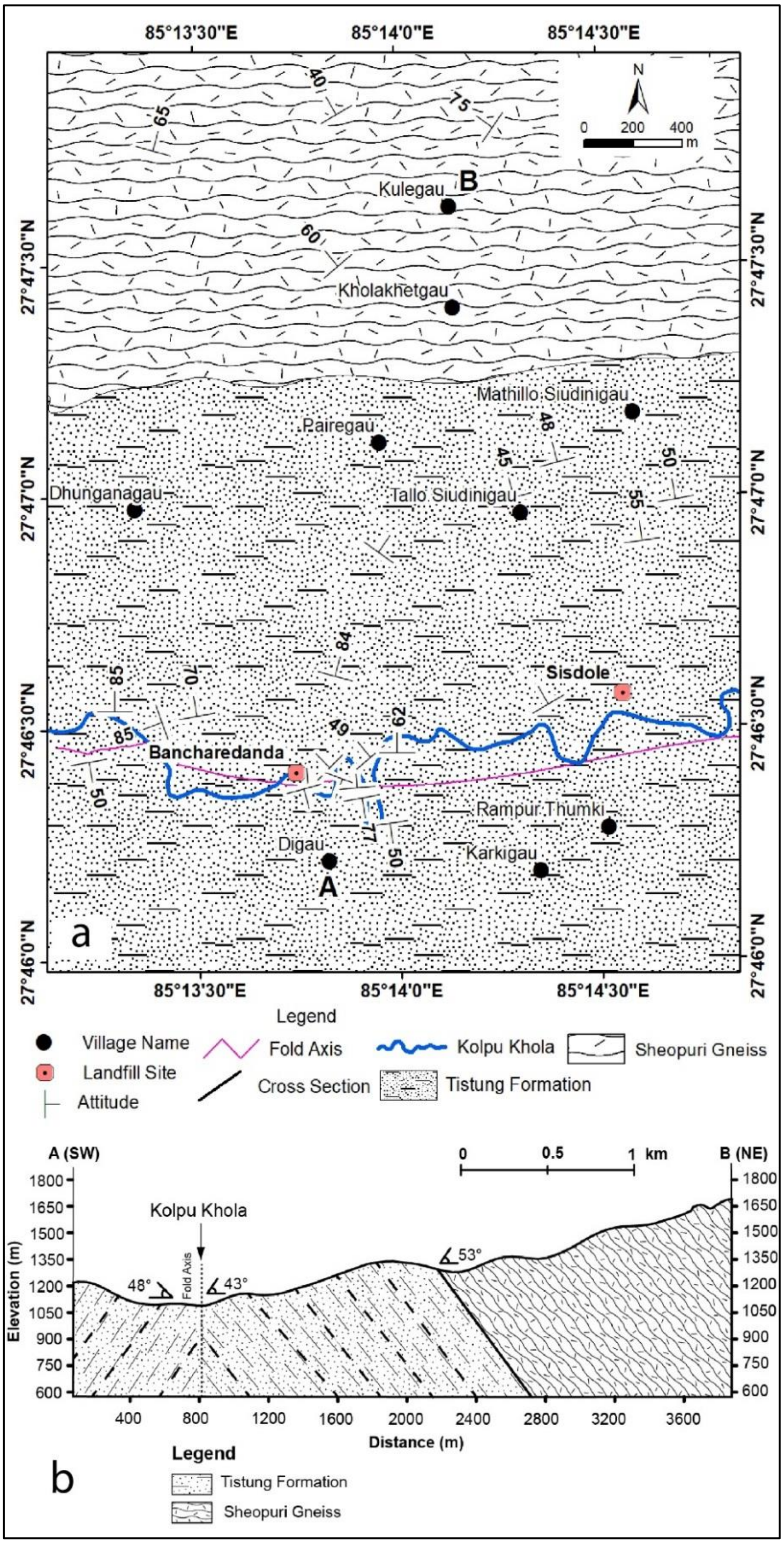

Figure 5: Geological map and cross-section; (5a): Geological map of the study area, (5b): Geological cross section from A to B)

3.1.2 Sheopuri Gneiss

The name has been derived from the Sheopuri Lekh located in the Shivapuri Nagarjun National Park of Kathmandu district. It is interfingered with the Tistung Formation and becomes continuous towards the North. The gneiss is associated with big pegmatitic and granitic intrusions. The gneiss is outcropped mainly in the northern part of the study area (Figure 6c and Figure 6d) namely Dulalgau, Kamale, Tallosiudani, Kholakhetgau, Kamigau, Kulegau and Manchhedada.

3.1.3 Geological Structures

In the Okharpauwa basin, beds of the Tistung Formation are apparently deformed (Figure 6e and 6f), presumably due to the influence of the adjacent gneiss intrusions. Rocks of this area shows influence of metamorphism which is justified by the foliation observed throughout. The Sheopuri Gneiss well exposes augen structure along with well-developed metamorphic foliation (Figure 6d). The geological cross section between the Kholakhetgau to Digau sections was prepared (Figure 5b). Two anticlines are observed in the study area. The Kolpu Khola flows from the axis of one of the local anticlines. The plot on dip 5.1 (Figure 7) found the trend and plunge of the fold axis to be $250^{o}/20^{o}$. Also, a local antiformal fold with EW trending limb (Figure 8) is observed on the left bank of the Kolpu Khola.

3.1.4 Laboratory Analysis of Samples

From the laboratory analysis, the unit weight and the strength parameters (cohesion and friction angle) of 9 samples were obtained. The results obtained from the laboratory analysis are presented in Table 1.

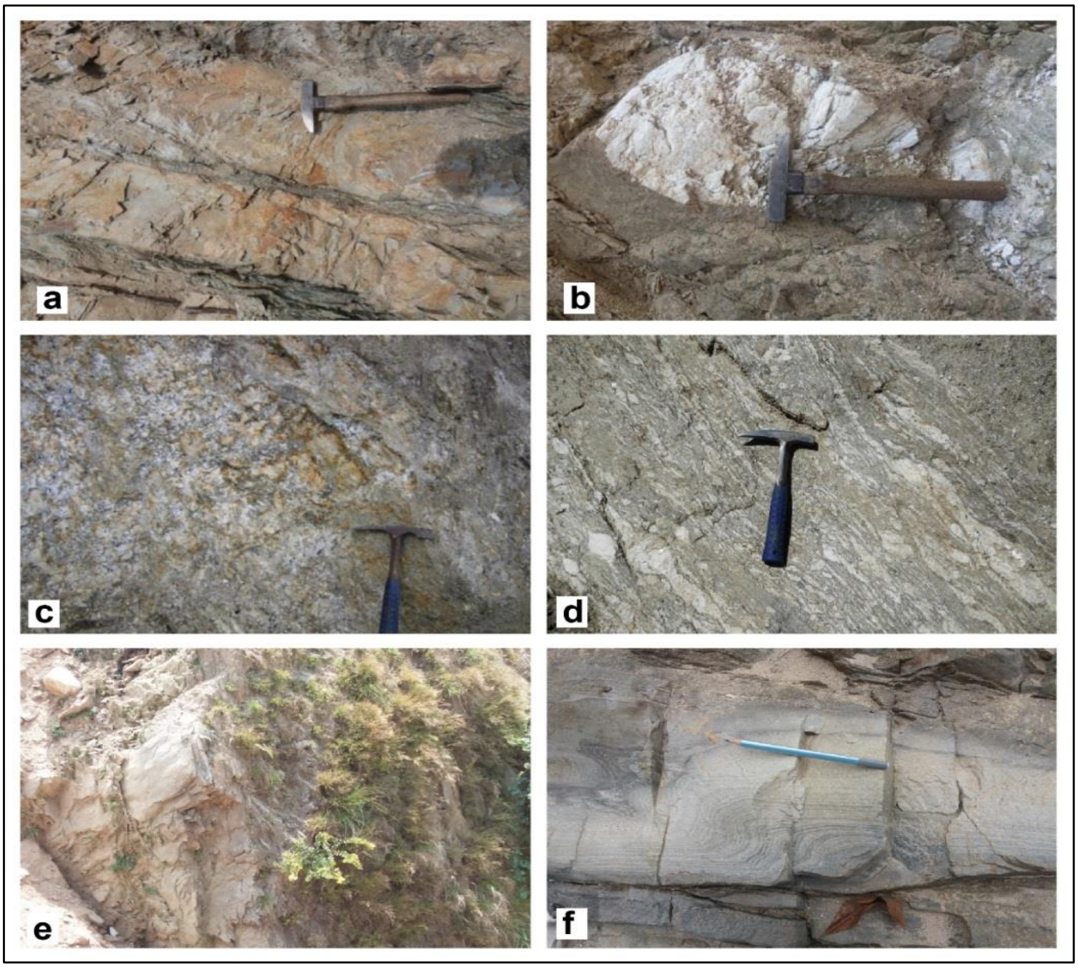

Figure 6: Photograph of a) Alternate sequence of weathered metasandstone and phyllite of the Tistung Formation at Banchare Danda (27°46'23.10"N, 85°13'48.92"E), b): Pegmatite dykes observed within theTistung Formation near the proposed Banchare Danda landfill site (27°46'24.13"N, 85°13'47.36"E), c) Weathered gneiss of the Sheopuri Gneiss observed at the Kulegau (27°47'40.96"N, 85°14'6.95"E), d) Gneiss exposed at the Kholakhetgau of the Sheopuri Gneiss (27°47'24.98"N, 85°14'4.82"E), e) Deformed metasandstone beds of Tistung Formation, and f) Folded lamina present on metasandstone observed on the right bank of the Kolpu Khola (27°46'24.20"N, 85°13'49.93"E)

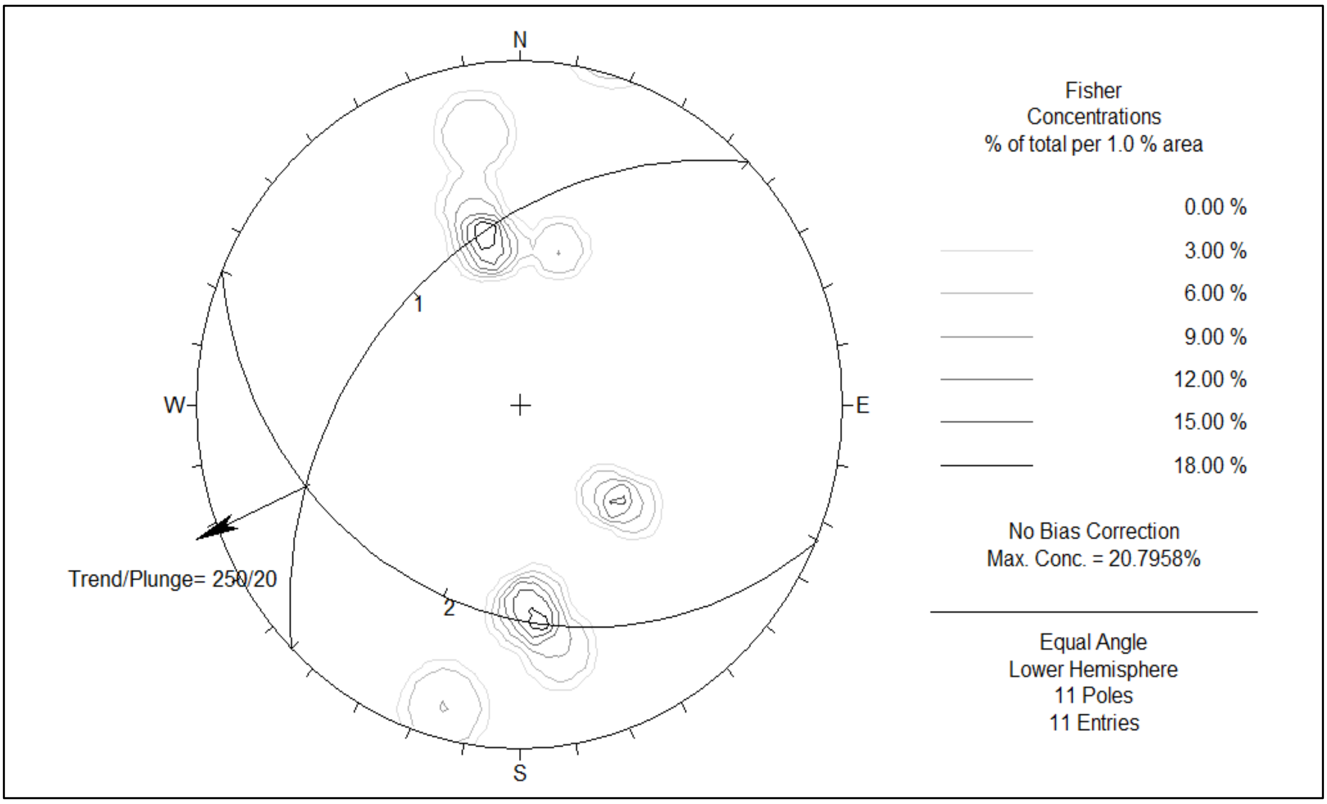

Figure 7: Dips plot to determine the orientation of the fold axis

Figure 8: Local scale antiformal structure observed on the left bank of the Kolpu Khola, (red lines represent dipping of beds).

3.2 Slope Stability Analysis

For the stability analysis, three vulnerable slopes of the landfill site were selected. The results of the laboratory analysis of 9 samples were used for the analysis. The slope stability analysis was performed for the landfill models with 3 different areas (Profile 1, Profile 2 and Profile 3) of slopes as shown in Figure 9. From Table 2, Samples S1, S12 and S11 were taken as Upper, Middle and Bottom waste layers for Profile 1. Samples S2, S4 and S6 were taken as Upper, Middle and Bottom waste layers for Profile 2. Samples S3, S10 and S5 were taken as Upper, Middle and Bottom waste layers for Profile 3. The analysis was carried out in the SLOPE/W a GeoStudio 2012 software in which deterministic (constant) and probabilistic analysis were carried out to determine the factor of safety.

Table 1: Soil properties assigned to different slopes

Sample No.		Unit Weight (kN/m^3)	Cohesion (kPa)	Friction angle (in degrees)
S1	Profile 1	12	8	32
S12		10	6	33
S11		18	8	30
S2	Profile 2	17	7	28
S4		16	9	25
S6		18	8	28
S3	Profile 3	17	4	29
S10		16	3	32
S5		17	13	28

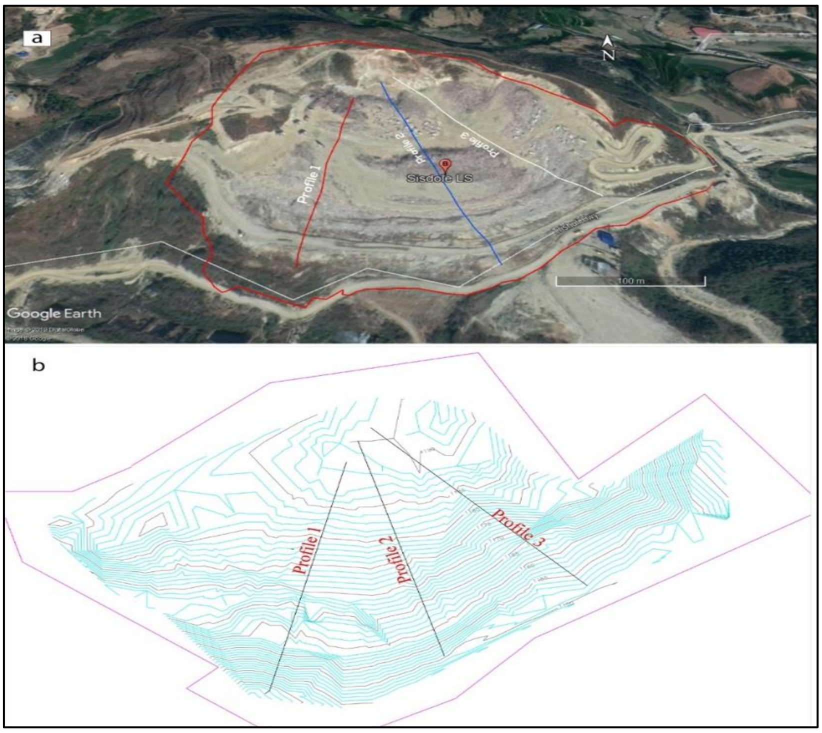

Figure 9: Three profiles taken for slope stability analysis: a) Profiles in Google Earth and b) Profiles in AutoCAD

3.3 Deterministic (Constant Method)

From the deterministic analysis, the computed factor of safety for the Profile 1, Profile 2 and Profile 3 were found to be 1.394, 1.396 and 1.391 respectively.

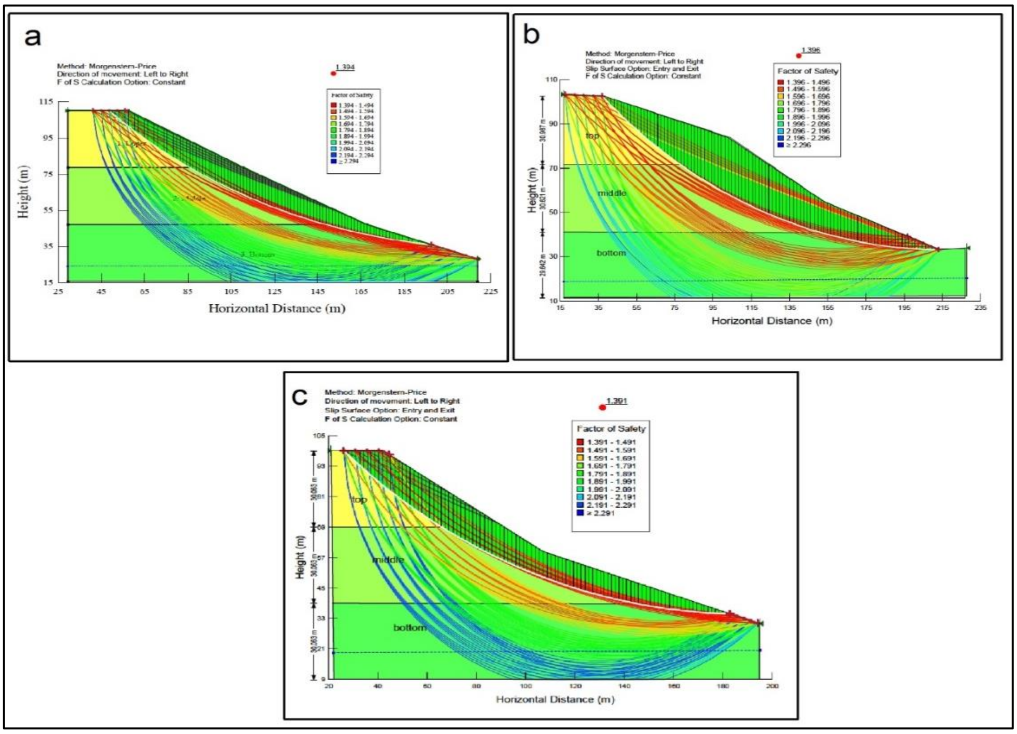

Figure 10: Result of slope stability analysis from deterministic approach (a) Profile 1, (b) Profile 2, (c) Profile 3

3.4 Probabilistic Analysis

After the deterministic analysis, probabilistic analysis was also carried out along the selected 3 profiles. Parameters like unit weight, cohesion and friction angle were assigned a normal probability density function for all 3 profiles. The normal distribution is the most important probability distribution in statistics because it fits many natural phenomena. Number of Monte Carlo Simulation trials were set to 2000. The results of the analysis are shown in Table 3. From the Figure 11, it shows that with increase in number of iterations the factor of safety versus frequency curve takes the shape of normal distribution curve and the reliability index becomes more or less the same. So the increase in number of iterations makes the result of analysis to be more precise and accurate.

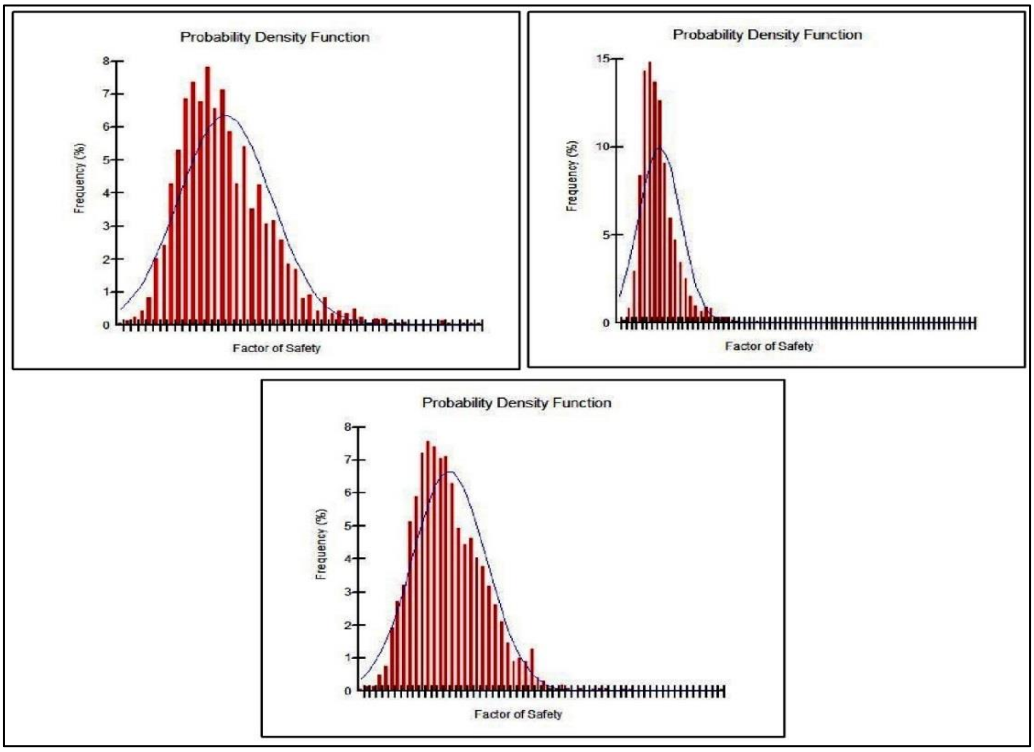

Figure 1: Factor of safety vs frequency from probabilistic approach (a) Profile 1, (b) Profile 2, (c) Profile 3

Table 2: Result of the probabilistic analysis of three slopes

Slope Profile	FoS	Probability of failure (%)	Reliability index	Standard Deviation
Profile 1	1.394	0	4.6796	0.74002
Profile 2	1.396	0	2.5607	1.1498
Profile 3	1.391	0	3.966	0.74704

Reliability Index represents the number of standard deviations which separate the mean Factor of Safety, from the critical Factor of Safety (= 1).

As a rule of thumb, the Reliability Index should be at least 3 or greater, to have reasonable assurance of a safe slope design. From Table 2, it is observed that all the 3 slopes have probability of failure 0 that means the probability of obtaining factor of safety less than 1 is 0. Also the Thus, the performance of Profile 1 and Profile 3 is higher compared to Profile 3. This is an indication that the Profile 1 and Profile 3 are safer than the Profile 2.

3.5 Seismic Analysis

The seismic coefficient values were assigned in 3 profiles and the change in factor of safety was calculated. The results of the seismic analysis showed decrease in factor of safety with increasing seismic coefficient (Table 3). The slopes of Profile 1 and Profile 2 become unstable for the seismic coefficient of more than 0.15 and .for Profile 3, the slope becomes unstable for seismic coefficient more than 0.2.

Table 3: Result of seismic analysis showing change in factor of safety with respect to seismic coefficient

Vertical and horizontal seismic coefficient	Factor of safety		
	Profile 1	Profile 2	Profile 3
0	1.394	1.396	1.391
0.025	1.316	1.306	1.304
0.05	1.247	1.23	1.232
0.075	1.187	1.163	1.169
0.1	1.133	1.105	1.114
0.15	1.043	1.009	1.022
0.2	0.969	0.932	0.947
0.25	0.907	0.869	0.885
0.32	0.855	0.817	0.834

4. Discussions

The geology of the Lesser Himalaya has been studied by many geoscientists previously. The classification done is adopted in the present study (Stöcklin and Bhattarai, 1977; Stöcklin, 1980). The study area lies in the Tistung Formation and Sheopuri Gneiss. The study of the rocks of the Tistung Formation showed the presence of metasandstone, phyllite with pegmatite dykes. The beds of the Tistung Formation is found to be apparently folded due to the influence of the adjacent gneiss intrusions called the Sheopuri Injection Gneiss. The exact correlation is with Dolp where he found the northern part of the Tistung Formation to be characterized by rocks of higher metamorphism, like mica shists and paragneisses (Dolp, 2014). In the present study area, the mica schist and paragneiss are found along the Kolpu Khola between Banchare Danda and Sisdole.

The unit is intruded by the Sheopuri Injection Gneiss (Stöcklin, 1980; Upreti, 1999). The quartzite bands, mentioned in Dhital, were not identified, due to the initial immaturity of sandstones, but the quartz veins were observed in the phyllite (Dhital, 2015). The geological cross-section showed the change in the dipping of the beds within the Tistung Formation indicating the presence of an anticline or more correctly antiformal structure along the Kolpu Khola and the proposed Banchare Danda landfill site lies near the core of the anticline or more correctly the antiformal structure. So, the proposed Banchare Danda landfill site is geologically unfavorable as the presence of anticline structures facilitates the movement of leachate and allows the contamination of the groundwater. The rocks present in the area are folded, fractured and weathered. So, the installation of geomembrane, geotextile is necessary to prevent the groundwater pollution. The installation of geomembrane, geotextile is necessary to prevent the groundwater pollution.

The factor of safety estimated by SLOPE/W for the landfill site for Profile 1, 2 and 3 were 1.394, 1.396 and 1.387 respectively for the circular failure. Comparing these values with the factor of safety of 1.5 which is often desired in geotechnical engineering, implies that the slope is not safe enough. Reason is the steep slope gradient in the working area (Shafer 2000). The geometry of the landfill site plays vital role in the stability. The retaining structures should be constructed to prevent the failure of the slopes of the landfill site. The factor of safety decreases considerably due to the seismic forces. The seismic coefficient more than 0.15 is found to be very hazardous for the stability of the landfill site. The reduction in shear strength of the slices after the application of the seismic forces is responsible for the decrease in factor of safety.

5. Conclusions

1. Two main lithological units were identified in the study area: the Tistung Formation and the Sheopuri Gneiss.
2. Local antiformal structure with fold axis along the Kolpu Khola was observed and the proposed Banchare Danda landfill site lies on the core of the antiformal structure.
3. From the stability analysis, factor of safety was found to be less than the desired value for all slopes. The slope is not safe enough and the reason is the steep slope of the landfill site.
4. The probabilistic analysis was carried out to determine the level of performance of the slope. The analysis showed that the Profile 2 has low performance than the Profile 1 and 3. So, the Profile 2 is unsafe.
5. The seismic analysis was carried out to find out the response of three slopes during ground shaking. The result showed slopes to be hazardous for seismic coefficient greater than 0.15. So, it is desirable to consider the seismic coefficient greater than 0.15.

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