



# Slope stability analysis of landslide zones in the part of Himalaya, Chamba, Himachal Pradesh, India

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## Abstract

The current study is related to the slope stability assessment along a part of pilgrimage route (NH-154A) connecting a holy shrines of Bharmour and Manimahesh. This road section also connects with hydroelectric dams and power stations through a tunnel. The recognition of the soil slopes has been done along the road corridor, thereafter, topographical and geotechnical based investigations were carried out along the failed soil slope sections. The soil samples were collected from each selected site for geotechnical studies. In general, the slopes with an inclination angles varying from 40°–80° were identified in the study area. Using circular failure charts (CFC), the factor of safety values were obtained based on the requisite parameters of the slope. The current study will be helpful for mitigating unstable slopes along the highway stretch. The slope steepness, proximity to river Ravi, rainfall, and human disturbance due to road widening are major triggering factors for slope instability along NH-154A.

**Keywords** Slope failure · Circular failure chart · Factor of safety · National Highway · Mitigation

## Introduction

The landslide disaster is a well-known phenomenon that occurs in the Himalayan terrain which is the most active topographic belt worldwide. The complex tectonic settings, steep slope profiles, higher elevation, and highly fragile terrain are the main causes of the slopes instability (Anbalagan 1992; Gupta and Sah 2008). The nature of the surface on the basis of weathering, drainage, and fracturing conditions are also some factors which influence the slope stability. The impact of natural hazards on the transport road networks and infrastructure is causing loss of life due to which various authors have adopted such studies (Chousianitis et al. 2016; Bathrellos et al. 2017; Skilodimou et al. 2019). Major lifeline road stretches often get blocked due to landslide activities worldwide. The landslides occurrence can be

analyzed through geotechnical, mineralogical, and chemical properties of the soil forming slopes. Hence for the detailed slope stability analysis, extensive field surveys including geometric characteristics of the slides, geomorphology, and geotechnical parameters are necessary to understand the mechanism of slope failure activities. During the last century, many geologists have dealt too with slope failure mechanisms (Bishop 1955; Janbu 1980; Hoek and Bray 1981; Rozos et al. 2011; Wei et al. 2012) and landslide hazard assessment (Ersoz and Topal 2018; Husain et al. 2019; Bathrellos et al. 2017; Skilodimou et al. 2019 Jana and Matej 2020). 20 road cut slopes in North West Black Sea region of Turkey were analyzed by employing slope stability probability classification method (SSPC). A slope mass rating method (SMR) was also adopted to identify grade of stability at each selected slope to compare the results of SSPC (Ersoz and Topal 2018). The earthquake induced landslide hazard in Greece is evaluated by means of a parametric time probabilistic approach. The derived slope strength demand maps could provide the basis for the assessment of whether particular slopes have a significant failure probability by comparing the estimated strength demand with the actual critical acceleration values calculated from slope material properties and slope angle (Chousianitis et al. 2016).

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Various slope stability methods viz. analytical, limit equilibrium, finite element, charts depend upon different modes of failures (Hoek and Bray 1981; Chung and Fabbri 1999; Zhu et al. 2003; Ermini et al. 2005; Gurocak et al. 2008; Hammouri et al. 2008; Michalowski 2010; Xu 2011; Shen et al. 2013; Kanungo et al. 2013; Eid 2014; Sarkar et al. 2016; Jamir et al. 2017; Dudeja et al. 2017; Kumar et al. 2018). However, the outcomes, and success of these methods depend upon their reliability (Bahsan et al. 2014). A review of these approaches of slope stability has been carried out by Fredlund and Krahn (1977) and Jing (2003). A detailed field database related to soil and rock properties, hydrogeological field conditions, and various landslide causative factors are the basic requirements for using these slope stability techniques. The most of the rocks contain clay minerals which have an important role in controlling various characteristics like permeability, water saturation, fracturing (Nara et al. 2012), shear strength (He et al. 2019), and slope stability (Hoek and Bray 1981; Harp et al. 1990; Reeuwijk 1993; Wieczorek 1996; Iverson 2000; Springman et al. 2013; Castro et al. 2020). Clay minerals might cause permeability reduction, due to their tendency to migrate and hence, plug interconnecting pore throats. Slope instability studies in the state of Himachal Pradesh, India have also been done by various authors (Sah and Mazari 1998, 2007; Anbalagan et al. 2008; Sarkar et al. 2009, 2016; Sharma et al. 2013; Bagri et al. 2016; Mahanta et al. 2016; Singh et al. 2017; Kumar et al. 2018). The selected site, for the present study, lies in the state of Himachal Pradesh state which is tectonically active and often remains disrupted due to natural disasters. Unpredictable cloud bursts, heavy rainfall triggering flashfloods, and landslides consume many lives every year in the state. Recently on 13th august 2017 about 48 people died during a massive landslide on Pathankot—Mandi National Highway (NH-154) in Himachal Pradesh (India), when 250 m road and two government buses were washed away because of the debris flow. Landslides in the state of Himachal Pradesh may become active due to cloud burst, rainfall, and seismic activities resulting into downward movement of the slope forming materials. The study area lies in district Chamba, Himachal Pradesh, India along the banks of river Ravi where landslides often get initiated during rainfall season affecting socio economic development of the region. Therefore, the pre-disaster management strategies are needful to cope with the hazardous conditions like landslides. These pre-disaster studies are related to the intensive field surveys, GIS based mapping and stability analysis of potentially unstable slopes whereas the post disaster studies are on the basis of back analysis of unstable slopes to find out the cause of slope failure (Gupta et al. 2016).

The road corridor NH-154A often gets disturbed due to landslides during monsoon season which also affects traffic flow. Various sites were observed as unstable which are

predominantly affecting transportation and developmental activities on the highway. Pilgrims visiting Manimahesh temple often get stuck at NH-154A due to rainfall triggered landslide activities which sometimes leads to death. Therefore, slope stability analysis is necessary for pre and post disaster management along the transport route. The current study deals with detailed geotechnical investigations, and assessment of the slope stability along NH-154A in Himachal Pradesh, India. The stability of the soil slope sites has been analyzed using circular failure charts (CFC) and based on the factor of safety calculated, the mitigation measures were suggested which will be beneficial to various stakeholders like planners and engineers.

## Description of the study area

### Location

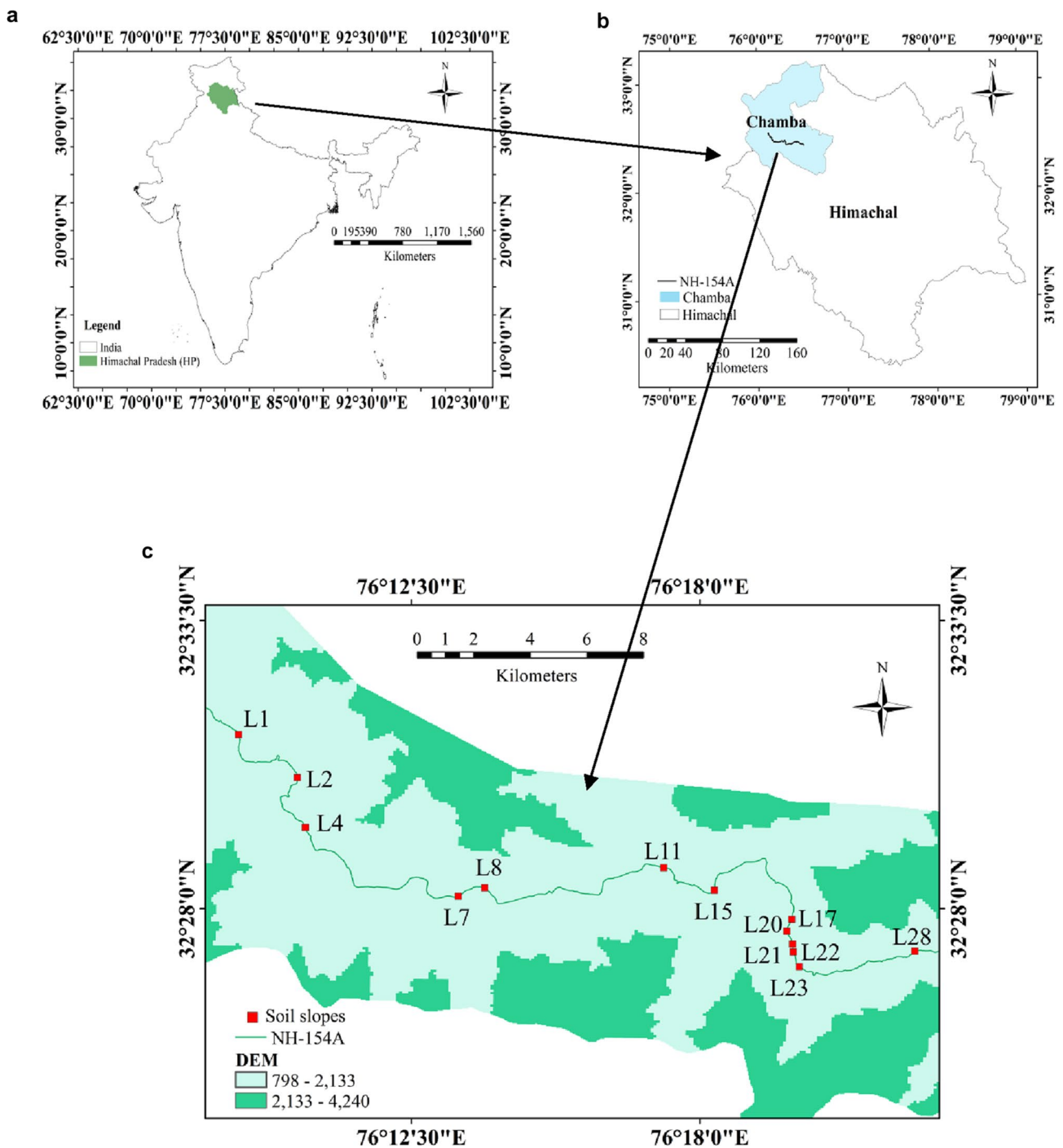
The study area lies in the Chamba district of Himachal Pradesh state (India) along Chamba – Bharmour NH-154A. The starting (from Chamba city) and the end coordinates (Temple town of Bharmour city) of the selected 62 km long NH-154A are 32°33'12.24"N, 76°7'32.88"E, and 32°26'34.08"N, 76°31'58.44"E. The study area (Fig. 1) is located on the toposheet numbers 52D/2, 52D/3, 52D/6, 52D/7, 52D/10, and 52D/11 available from Survey of India (SOI). The route includes a tunnel also, which is located at Chamera III hydroelectricity dam with the coordinates 32°28'15.75"N, 76°26'10.51"E and 32°28'21.70"N, 76°26'24.46"E. The most common languages of the area are Hindi, Bhattiyali, Dogri-Kangri, and Pahari.

### Physiography

The Chamba region is highly mountainous with altitudes ranging between 609 and 6402 m. An average seasonal temperatures vary from 15°C (59°F) to 38°C (100°F) in summer and to 0°C (32°F) to 15°C (59°F) in winter. The average annual rainfall in the area is 785.84 mm (30.939 in). The selected corridor passes along the banks of river Ravi from Bharmour town towards Chamba city. The river Ravi is a trans-boundary river passing through northwestern India and Pakistan. The major cities on this corridor are Dalhousie, Dharamshala, and Pathankot. A very famous ancient Trilochan Mahadev Temple is at a distance of few meters from Lothal village landslide.

### Geology

The geology of the Chamba region is the combination of the wide range of the rock formations of age from late Proterozoic to Triassic. The sequence of these rocks has been



**Fig. 1** Location map of study area **a** Map of India and Himachal Pradesh **b** Himachal Pradesh state and district Chamba **c** Selected unstable soil slopes along NH—154A and Digital Elevation Model (DEM) of the study area

classified as lower and upper in literature. Table 1 is showing the geological sequence of the Chamba region (Srikantia and Bhargava 1998). The Batal Formation composed of Manjir Conglomerate overlies Chamba Formation (Salkhala Group) in the study area. The Salkhala Group is surrounded by Vairkrita Group and Katari Gali formations in Chamba region.

The Salkhala group has been classified into the Formations of Chamba and Bhalai by Rattan (1973).

The Bhalai Formation, Chamba Formation, Manjir Formation, Batal Formation, Katarigali Formation, Mandi granites are present in the area regionally whereas along the NH-154A, quartzites, slates, and gneiss rocks exists locally

**Table 1** Geological sequences of Chamba area (Srikantia and Bhargava 1998)

Kalhel Formation (Triassic)	Greyish blue, grey and yellow limestone and dolomite with interbedded grey ortho quartzite in the upper part. Grey calcareous shale with interbeds of limestone in the basal part
Salooni Formation (Permian)	Dark grey or black carbonaceous pyritous slates with thin lenticles of limestone at places. There are discontinuous bands of varying thickness of amygdaloidal and massive lava flows of basaltic to andesitic composition
Unconformity	
Batal Formation also called Katari Gali Formation (Terminal proterozoic)	Black carbonaceous phyllite with interbeds of quartzite. Local limestone bed at the base with magnesite and scale of gypsum
Manjir Formation	Polymictic diamictite – poorly sorted, lithologically heterogeneous, laminated or banded
Unconformity	
Chamba Formation (Salkhala Group) Meso-proterozoic	Dark grey, thinly bedded laminated slates with subordinate bands

(Fig. 2). At a few places, river born material, and conglomerates have also been observed. During reconnaissance, it was observed that the selected corridor is passing through two types of geological material, namely, in-situ rocks and soil/debris (overburden). Hilly terrain of the study area is mainly composed of metamorphic rocks. Rocks are weathered near surface as seen in the cut slopes of NH-154A. Weathered rocky terrain is there in the field along the NH-154A. A clear exposure can be observed on cut slopes showing well developed discontinuities in the form of foliations and joints.

### Field observations: slope failure characteristics

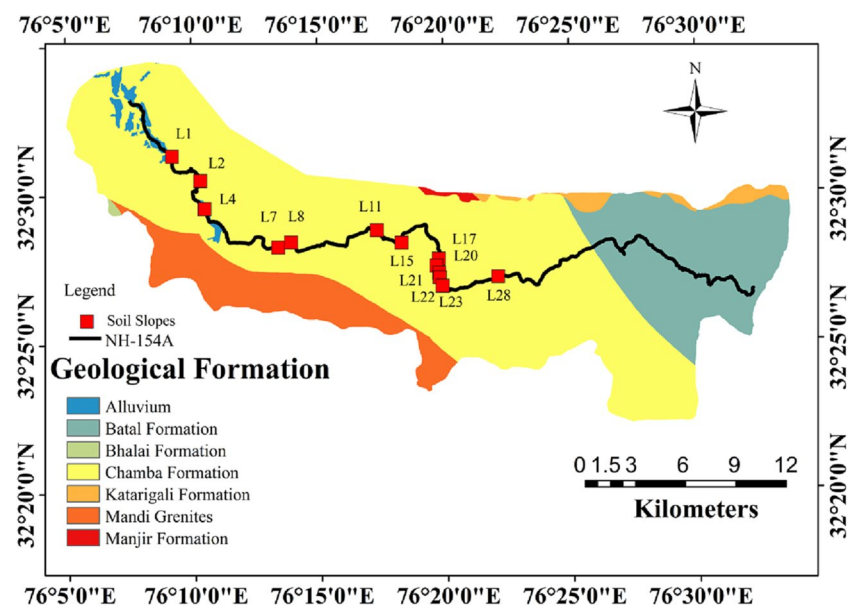
Landslides along the NH-154A often becomes active during rainfall from past few years. The sparsely vegetative and barren slopes, which are potentially unstable have been observed along the road section. A huge rotational type

of failure was observed at Lothal village along NH-154A, which is a potential danger to a hydroelectric turbine linked with a penstock at a few meters distance from the current landslide. The rainfall triggered landslides in the study area often caused road blockage along the NH-154A during every monsoon. Toe cutting along river Ravi may also be identified due to high discharge during rainfall.

### Methodology

The selection of locations has been carried out in those areas which were observed to be potentially vulnerable due to unstable slopes to further analyze their stability. These slopes were selected by observing slope inclination, material characteristics, and subsurface water conditions through extensive field visits. Thereafter, the slope stability assessment of the soil slope sections has been carried out using

**Fig. 2** Geological formation map of the study area



circular failure chart (CFC) to determine the factor of safety of the slopes. The stability analysis performed using CFC depends upon the shear strength parameters of the soil. The type of movement of landslides, nature of slope forming material, and gradient of slope helped to decide type of landslide.

During the field survey, in case of soil slopes along the NH-154A, the failure plane taking a circular path has been observed which also known as rotational or circular failure. The failure plane of this type in case of soil and debris slopes is free to find the path of least resistance and hence tends to take a circular path. In the study area, a total of 13 soil slope sites L1S1, L2S2, L4S3, L7S4, L8S5, L11S6, L15S7, L17S8, L20S9, L21S10, L22S11, L23S12, and L28S13 which are having potential of circular failure were selected for their stability evaluation (Fig. 3, Table 2). The naming of the selected soil slope sites has been done in terms of LS, showing location number L and soil slope S. These highly crushed and weathered slope sites are important from the point of view of stability along the highway because they are predominantly disturbing the road connectivity and constructional activities in the area. A field survey was performed for collecting geometrical and geotechnical inputs along these soil slope sections to further analyze stability in detailed manner to calculate their factor of safety.

The profiles of the slide zones have been prepared by marking their section. Geometric dimensions of the slides have been measured with the help of 100 m tape while the elevation, latitude and longitude of the slides were obtained from Global Positioning System (GPS). The location of the landslide has also been marked on the toposheet of scale 1:50,000 developed by Survey of India (SOI). These are the soil slopes hence there is not strongly defined structural pattern on which the failure occurred thus a least resistance line is free to find in such case.

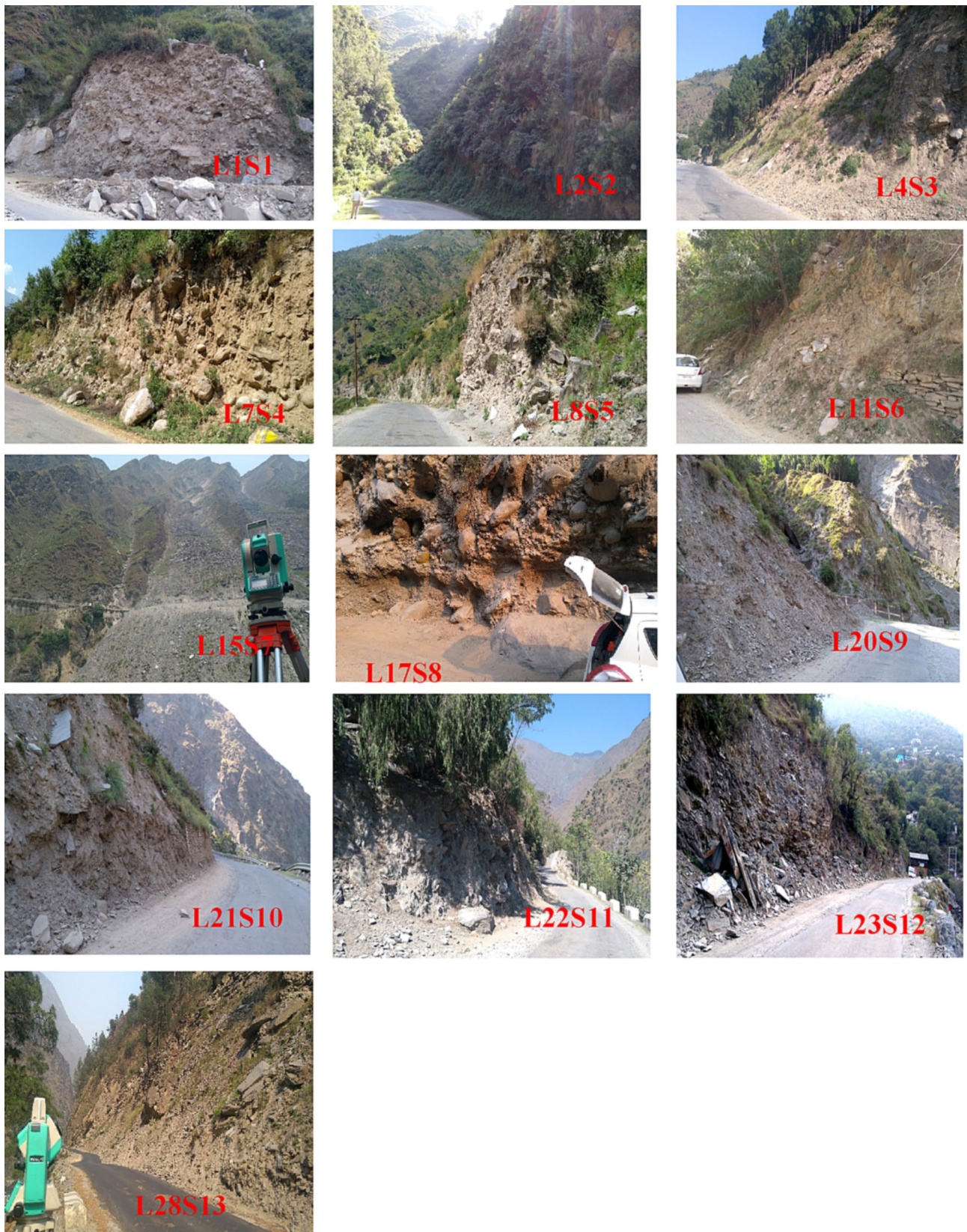
The crown of landslide can be localized below the hill top in case of circular failure whereas the toe portion may get located either on or above the river bed. If the circular failure is happening through the toe of the slope, the center of the critical circle can be located using toe and head of the slide. Accordingly, an arch can be drawn in the profile (Hoek and Bray 1981).

The soil samples have been collected from the selected slides from the marked sections to determine the moisture content, unit weight, and shear strength parameters of cohesion ( $c$ ) and friction angle ( $\phi$ ) in accordance with the procedure mentioned in the Indian standards (IS). The water content determination was done by adopting (IS: 2720 Part 2–1973). The dry sieve method was conducted for the grain size analysis as per (IS: 2720 Part 4–1985). The ( $c$ ) and ( $\phi$ ) values have been obtained from the direct

shear test as per (IS: 2720 Part 13—1986). The shearing of the soil samples was done by applying normal loading of 0.5, 1.0, and 1.5 kg/cm<sup>2</sup>. These soil properties thus calculated were used as the input datasets for the slope stability assessment using CFC to determine FOS value for the slope which can be defined as the ratio of the total resisting force along the plane of the separation and the total mobilizing force initiating failure. The stability of the slope depends upon the equilibrium conditions between the forces resisting and mobilizing the sliding which should also be equal to make FOS as unity. The slope will be more stable in case of FOS value more than unity while slope will indicate failure if the FOS value will be less than one.

By taking an assumption that the slope material is uniform throughout the slope, the FOS value of the selected circular failure slide zones has been determined using Circular Failure Charts (CFC) proposed in Hoek and Bray (1981), which is based on the varying ground water conditions (Fig. 4). As per Hoek and Bray (1981), the factor of safety of the slope can be analyzed by assuming the moisture percentage in the slope i.e. 0%, 25%, 50%, 75%, and 100% based on the CFC charts which they have proposed. A moisture range from dry to fully saturated slope conditions was prescribed in CFC charts and is numbered as 1–5 in accordance with the saturation of water in the slope (Hoek and Bray 1981). The selection of the circular failure charts depending upon the ground water conditions which may varies as per the observed conditions of the slope in the field and for the prediction conditions. For each soil slope site, first three charts (1, 2, and 3) were selected for completely dry, 25%, and 50% moisture conditions. During rains, the slope surface is saturated and the sub surface seepage is much limited and the general saturation level is on an average is less than 25%. It is applicable to the most of the cases. However, in extremely high concentrated rainfall taking place over long duration, the percentage may go up more than 25%. At each slope section, a minimum of five disturbed soil samples from 50 cm depth, and a few undisturbed soil samples in the form of cores were collected for detailed laboratory testing. The parameters required for CFC are namely cohesion ( $c$ ), friction angle ( $\phi$ ), slope angle, slope height ( $H$ ), and soil density ( $\gamma$ ) to determine FOS. A dimensionless ratio  $\frac{c}{\gamma H \tan \phi}$  has been determined based on the above parameters which can be marked on the outer periphery of each chart (Fig. 5).

After locating the dimensionless ratio, one should have to follow the radial line as shown in Fig. 5 up to the corresponding value of slope inclination to determine values of X and Y intercepts. The average values of cohesion and friction at each site were considered to evaluate factor of safety along X and Y intercepts.

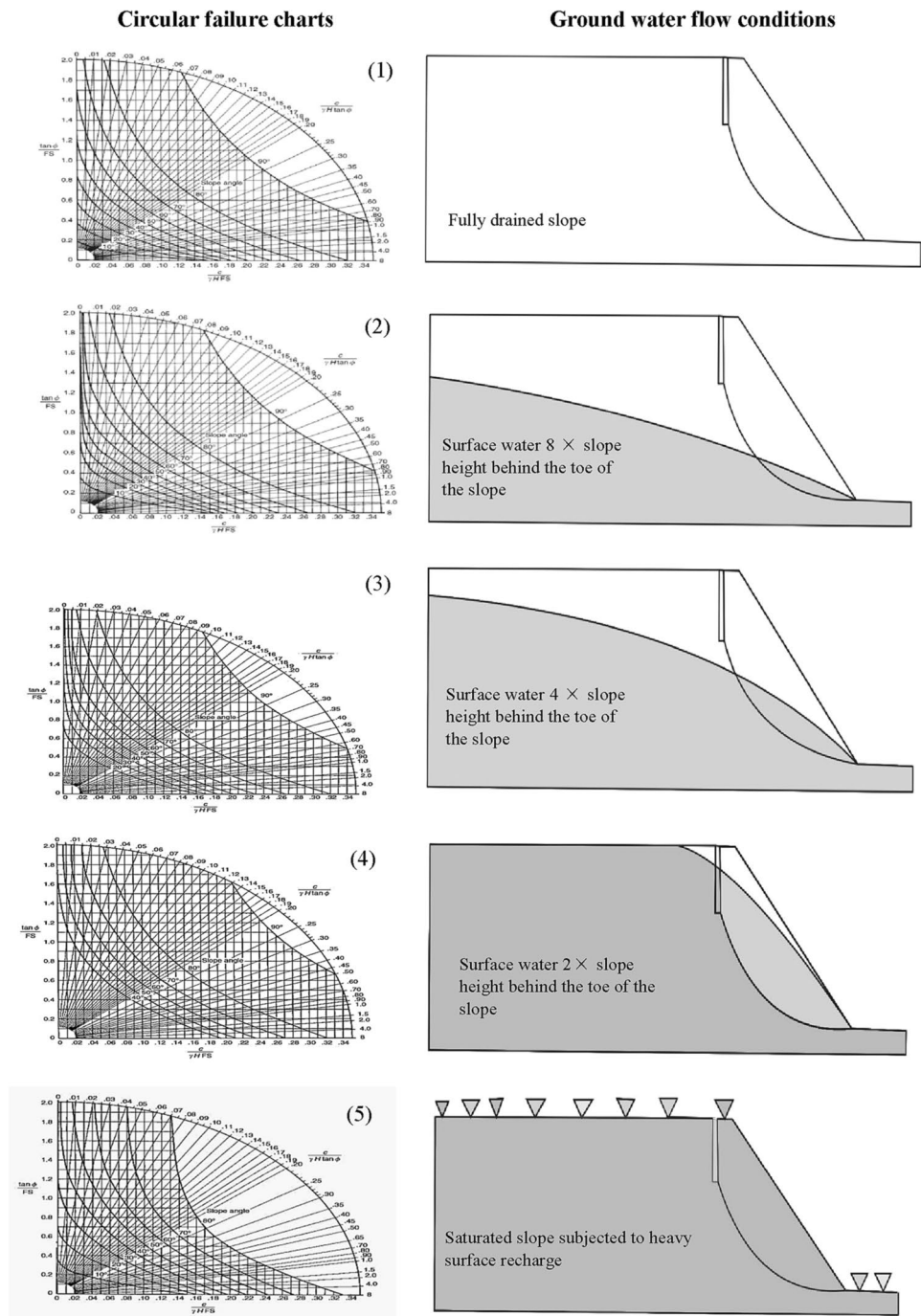


**Fig. 3** Field photographs of the soil slope sections along NH-154A where in LS, L and S represent location number and soil slope respectively

**Table 2** Location of selected soil slopes

Location no.	Latitude/longitude	Elevation (m)	Location	Vegetation Cover	Slope attitude	Landslide dimension	Approximate volume (m <sup>3</sup> )	Historical data
L1S1	32°31'19.4880"N, 76°09'12.4920"E	923.54	Near to the Chamba township	Barren slope, Sparsely vegetated above crown	70°/N250°	About 15 m along the road stretch	~ 600	Frequently occurring landslide area during heavy rainfall
L2S2	32° 30'29.9780"N, 76°10'19.5480"E	998.52	Just about the NHPC power house	Moderately vegetated	60°/N	About 50 m along the road stretch	~5700	Mainly occurs during heavy rainfall
L4S3	32°29'32.0100"N, 76°10'28.9800"E	993.64	About 2 km from Rajera village towards Bharmour	Sparsely vegetated with trees above crown	50°/N220°	About 40 m along the road stretch	~2900	Mainly occurs during the rains
L7S4	32°28'13.8900"N, 76°13'23.7000"E	1133.85	After crossing Kalsuin village towards Bharmour	Barren slope with sparsely vegetated cover above crown	80°/N160°	About 15 m along the road stretch	~ 900	Mainly occurs during heavy rainfall
L8S5	32°28'23.9880"N, 76°13' 52.3800"E	926.59	Near Rakh village	Barren slope with sparsely vegetated cover above crown	80°/N200°	About 25 m along the road stretch	~ 1500	Mainly occurs during heavy rainfall
L11S6	32°28'47.1480"N, 76° 17' 18.8400"E	1157.63	Nearby the Chamera power house at Mokhri village	Barren slope with sparsely vegetated cover above crown	50°/N10°	About 25 m along the road stretch	~ 1375	Mainly occurs during heavy rainfall
L15S7	32°28'21.3960"N, 76°18' 15.4560"E	1206.70	At Lothal village	Barren slope	40°/N295°	About 300 m along the road stretch	~ 534,000	Remained a prominent slide zone
L17S8	32°27'46.0500"N, 76°19'43.3180"E	1223.77	At 1 km distance from Dunali village towards Chamba	Barren slope with sparsely vegetated cover above crown	80°/N345°	About 15 m along the road stretch	~ 1500	Mainly occurs during heavy rainfall
L20S9	32° 27'32.6560"N, 76°19' 40.9920"E	1345.69	About 300 m before Dunali village towards Chamba	Barren slope with sparsely vegetated cover above crown	50°/N50°	About 22 m along the road stretch	~2200	Mainly occurs during heavy rainfall
L21S10	32°27'19.5780 "N, 76°19'45.77"E	1420.36	About 240 m from Dunali village towards Chamba	Barren slope with sparsely vegetated cover above crown	50°/N90°	About 10 m along the road stretch	~ 610	Mainly occurs during heavy rainfall
L22S11	32°27'10.3032"N, 76°19' 47.4960"E	1303.32	Near Gehra village	Barren slope with moderately vegetated cover above crown	50°/N105°	About 15 m along the road stretch	~ 825	Mainly occurs during the rains
L23S12	32°26'53.35"N, 76° 19 '53.65"E	1386.84	At Gehra village	Barren slope	60°/N50°	About 13 m along the road stretch	~975	Mainly occurs during heavy rainfall
L28S13	32°27'11.820"N, 76°22'05.7780"E	1278.02	About 4 km from Gehra village towards Bharmour	Barren slope with sparsely vegetated cover above crown	50°/N330°	About 40 m along the road stretch	~5960	Mainly occurs during the rains

**Fig. 4** Circular failure charts used for the assessment of slope stability at varying ground water condition (Hoek and Bray 1981)



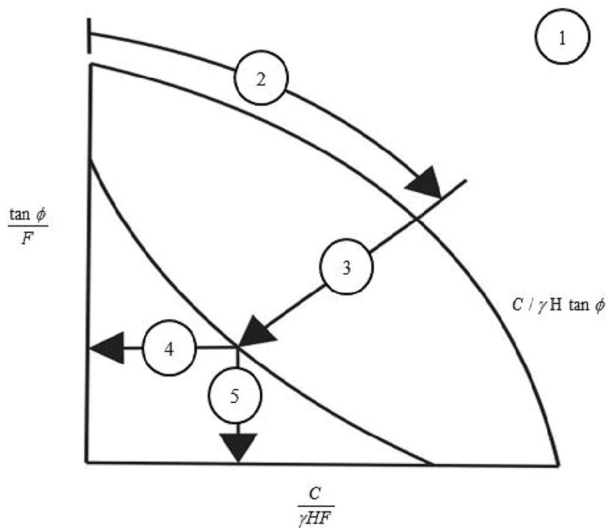
**Results and discussions**

The varying thickness of the soil overburden from about 0.5 m to 10 m along NH-154A fulfill the criteria for circular failure. The circular failure charts were used for the slope stability assessment because of its simplicity, and time-saving. The bulk unit weights (conforming IS: 2720 PART XXIX-1975) of various soil samples were determined in the laboratory. The soil of various slope sites was then classified as well graded sand (SW) using grain

size analysis curves (Fig. 6) conforming to IS: 2720 PART IV-1985. The average size  $D_{50}$ , effective size  $D_{10}$ , uniformity coefficient ( $C_u$ ) and coefficient of curvature ( $C_c$ ) of various soil samples obtained from these gradation curves are given in Table 3.

The shear strength parameters of the soil were obtained by applying three different normal loads of (0.5, 1.0, and 1.5 kg/cm<sup>2</sup>) in a direct shear test. The outcomes in the form of normal stress and shear stress were plotted to determine cohesion and friction as per IS: 2720 part 13 (1986) and are





**Fig. 5** Stepwise sequence in the circular failure charts to calculate factor of safety

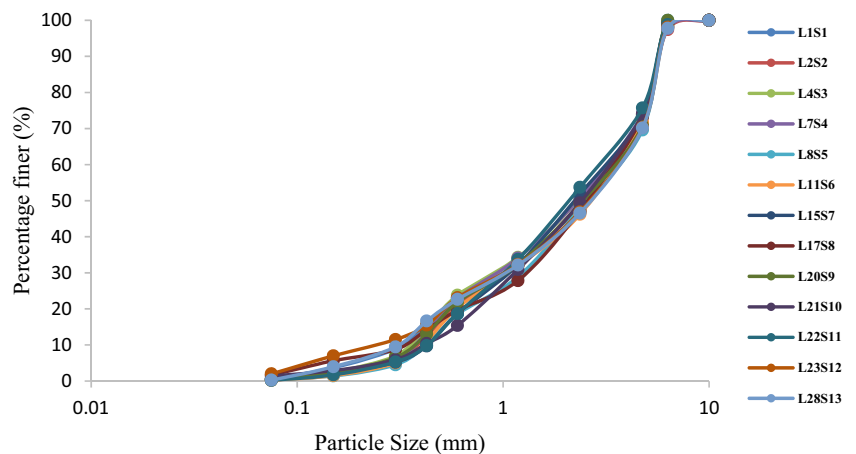
given in Table 4. The FOS value for each slope section has been determined based on the inputs as given in Table 5.

**Slide description and analysis**

**Slope section—L1S1**

This soil slope is located near Chamba Township. The road has been cut within the debris soil overburden. On an average the height of the cut slope ranges up to 8 m. Though it varies from 4 to 8 m. The cut slope is nearly vertical (70°). The thickness of the overburden is high ranging from 12 to 18 m. A fresh cut slope of debris/assorted size material consisting of silty clay matrix was observed at this location. The slope, in general, is damp, and has a sudden change in gradient at places. The upper slope supports a good vegetation cover of bushes and a few trees. The inclination of the upper slope is about 30°- 40°. The factor of safety evaluated has been given in Table 5. The FOS value showed that the slope is just stable under 0% and 25% moisture conditions, whereas it may become unstable when the saturation level starts increasing.

**Fig. 6** Particle size distribution curves of soil samples from selected site



**Table 3** Particle size distribution analysis (IS: 2720 PART IV-1985)

S. No	Location	$D_{10(mm)}$	$D_{30(mm)}$	$D_{60(mm)}$	$D_{50(mm)}$	$C_u$	$C_c$	Classification
1	L1S1	0.29	1.00	3.4	2.6	11.72	1.01	SW
2	L2S2	0.28	1.20	3.5	2.5	12.50	1.47	SW
3	L4S3	0.28	0.97	3.3	2.4	11.80	1.02	SW
4	L7S4	0.29	0.95	3.1	2.4	10.69	1.00	SW
5	L8S5	0.33	1.30	3.8	3.0	11.50	1.35	SW
6	L11S6	0.4	1.20	3.6	2.6	9.00	1.00	SW
7	L15S7	0.42	1.20	3.2	2.3	7.60	1.07	SW
8	L17S8	0.32	1.40	4.7	2.6	14.70	1.30	SW
9	L20S9	0.38	1.20	3.6	2.5	9.50	1.05	SW
10	L21S10	0.38	1.10	3.2	2.5	8.40	1.00	SW
11	L22S11	0.42	1.20	2.9	2.2	6.90	1.18	SW
12	L23S12	0.25	1.00	3.8	2.6	15.20	1.05	SW
13	L28S13	0.31	1.10	3.7	2.7	11.90	1.05	SW

**Table 4** Shear strength parameters of soil samples collected from selected sites

Location	Sec A-A/a		Sec A-A/b		Sec A-A/c		Sec A-A/d		Sec A-A/e		Average value	
	c (kPa)	$\phi$ (°)	c (kPa)	$\phi$ (°)	c (kPa)	$\phi$ (°)	c (kPa)	$\phi$ (°)	c (kPa)	$\phi$ (°)	c (kPa)	$\phi$ (°)
L1S1	9.8	30	14.7	29.5	16.18	30.5	20.3	30	19.05	30.4	16.0	30.08
L2S2	20	31	21	30	19	30	18	29	22	30.2	20	30.04
L4S3	9.8	35	11.76	30.3	10.78	30.2	10.6	32	11	32.5	10.7	32
L7S4	22	31.79	21	30.11	20	29.29	22	32	25	26.9	22	30.01
L8S5	19	34.99	18	34.99	22	35.37	21	37	22	33	20.4	35.07
L11S6	10	29	10.2	32	11	29.5	11	31.5	8	33.2	10.04	31.04
L15S7	4.9	36.86	15.69	33.02	14.7	38	10.55	32.4	13	35	11.76	35.05
L17S8	38	26.9	36	26	41	25.17	40	26.2	45	26	40	26.05
L20S9	18.5	35	20	36	10.9	34.21	11	35	10	35.1	14.08	35.06
L21S10	15	30	14	30.54	12	30	16	30	18	31	15	30.30
L22S11	16	34.09	19	31.79	18	30.54	22	32	25	31.7	20	32.02
L23S12	22	31	21.5	29	15.7	31	24.5	31	26.3	33	22	31
L28S13	12.74	30.92	14.2	30.32	15	33.62	11.1	32	12	28.5	13.00	31.07

**Table 5** Input parameters and factor of safety based on CFC

Location	Parameters					Factor of safety (CFC)		
	Cohesion of soil (C) kPa	Angle of friction ( $\phi$ )	Slope Inclination	Height of slope (m)	Unit weight of soil (KN/m <sup>3</sup> )	Chart 1	Chart 2	Chart 3
L1S1	16	30°	70°/N250°	8	18	1.06	1.02	0.97
L2S2	20	30°	60°/N	19	18.5	0.93	0.90	0.88
L4S3	10.78	32°	50°/N220°	14.5	18	1.036	1.000	0.915
L7S4	22	30°	80°/N160°	12	18	0.967	0.933	0.90
L8S5	20	35°	80°/N200°	12	18	1.05	1.03	0.98
L11S6	10	31°	50°/N10°	11	18.94	1.07	1.0	0.94
L15S7	11.76	35°	40°/N295°	178	18.87	1.359	0.920	0.864
L17S8	40	26°	80°/N345°	20	18	0.80	0.77	0.75
L20S9	14	35°	50°/N50°	20	18.88	1.117	1.029	0.930
L21S10	15	30°	50°/N90°	12.2	18.18	1.15	1.13	1.04
L22S11	20	32°	50°/N105°	11	18.88	1.43	1.38	1.29
L23S12	22	31°	60°/N50°	15	18.98	1.0	0.99	0.94
L28S13	13	31°	50°/N330°	29.8	18	1.05	0.951	0.830

#### Slope section—L2S2.

This soil slope is located just about the NHPC power house. The road has been cut within the debris soil overburden. On an average the height of the cut slope ranges up to 19 m. Though it varies from 15 to 19 m. The cut slope is inclined at 60°–70°. This slope consists of well graded debris material ranging from clay to sand. The entire slope is damp, and the bottom of the slope is generally wet. A thin vegetation cover of bushes was observed on the slope surface. Since the factor of safety for the slope comes out to be less than unity (Table 5), hence it as an unstable slope at all the three conditions i.e. completely dry conditions, 25%, and 50% saturation conditions.

#### Soil slope section—L4S3

This soil slope is located near about 2 km from Rajera village towards Bharmour along NH-154A. The road has been cut within the debris soil overburden. On an average the height of the cut slope ranges up to 14.5 m. The cut slope is inclined at 50°. The thickness of the overburden is high ranging from 11 to 19 m. The slope consists of debris material, and angular fragments of quartzite. The embedded material was found along with silt sandy matrix. The upper slope is supporting thick vegetation of trees and bushes. Rotational debris circular failure was observed on this slope. The loose debris material may fall during the rainy season. The factor

of safety value was determined equal to 1.036 and 1.0 for completely dry and 25% slope saturation conditions respectively, showing that slope is just stable for these conditions, whereas the slope becomes unstable at the stage of 50% moisture content for which FOS is 0.915 (Table 5).

#### Soil slope section–L754

This soil slope is located after crossing Kalsuin village towards Bharmour along NH-154A. The road has been cut within the debris soil overburden. On an average the height of the cut slope ranges up to 12 m. Though it varies from 8 to 12 m. The cut slope is nearly vertical (80°). The thickness of the overburden is high ranging from 14 to 20 m. This slope is alluvial cum colluvial slope. River-borne material have been found at the slope surface. Rounded and angular boulders along with the debris type of material were observed at this slope section. The upper slope supports thick vegetation in the form of trees and bushes. The slope surface is dry and barren in nature. There are chances of occurrence of the rotational type of failure at the current location. The factor of safety values are given in Table 5. All FOS values are less than one under all groundwater conditions.

#### Soil slope section–L855

This soil slope is located near Rakh village along NH-154A. The cut slope is nearly vertical 80° towards N200°. On an average the height of the cut slope ranges up to 12 m. Though it varies from 8 to 12 m. The thickness of the overburden is high ranging from 14 to 18 m. The inclination of the upper slope is 20°–30°. Assorted debris kind of material with the matrix of silty clay (60–70%) was found at the current slope. This is a well compacted dry slope which fulfills the conditions of circular failure. Upper slope supports good vegetation. There are chances of a rotational type of failure at this slope section during rainy season. The outcomes of the stability analysis revealed that the selected section of the slope is just stable at completely dry and 25% moisture condition with FOS value i.e. 1.05 at the completely dry slope, 1.03 at 25% saturation, and unstable at 50% saturation content with FOS value 0.98 as given in Table 5.

#### Soil slope section – L1156

This soil slope is located nearby the Chamera power house at Mokhri village along NH-154A. The road has been cut within the debris soil overburden. On an average the height of the cut slope ranges up to 11 m. Though it varies from 8 to 11 m. The cut slope is inclined at 50° towards N10° while the general slope is inclined at an angle about 30° towards N10°. The signs of erosion may be seen at the slope surface. The thickness of the overburden is high ranging

from 12 to 18 m. This is a completely dry and barren slope with an inclination of the upper slope about 20°–25°. The upper slope supports vegetation with bushes. The slope is showing signs of debris rotational failure. In case when the slope is 50% saturated, the FOS value is smaller than one, therefore the slope is unstable in that case. The FOS value is more than one in case of completely dry and one at 25% wet slope conditions, and hence indicates just stable character (Table 5).

#### Soil slope section–L1557

This soil slope is located near Lothal village along NH-154A. The road has been cut within the debris soil overburden, hence debris flow may occur in future due to excess rainfall. The cut slope is inclined at 40°. A massive debris circular failure was observed at this slope section. This is a barren slope having damp groundwater conditions. The hydroelectric features like hoses and penstocks are present a few meter from this site. The FOS values determined are given in (Table 5) which shows that the slope is stable with 1.359 value of FOS when it is dry, while the safety factor for other conditions comes out to be less than one. Hence, this landslide can become active during rainy seasons.

#### Soil slope section–L1758

This soil slope is located at 1 km distance from Dunali village towards Chamba along NH-154A. The road has been cut within the debris soil overburden. On an average the height of the cut slope ranges up to 20 m. Though it varies from 15 to 20 m. The cut slope is nearly vertical (80°). The thickness of the overburden is high ranging from 18 to 25 m. The slope consists of river born material like boulders and gravels, and fulfills the criteria for a circular failure to takes place. It has been observed that rock boulders start falling on the NH-154A due to heavy rainfall. The slope is barren and supports a few trees, grass, and bushes at the upper slope. The slope section is nearly vertical and has been found to be unstable because the FOS values as mentioned in (Table 5) are less than one for all the groundwater conditions.

#### Soil slope section–L2059

This soil slope is located at about 300 m before Dunali village towards Chamba along NH-154A. The road has been cut within the debris soil overburden. On an average the height of the cut slope ranges up to 20 m. The cut slope is inclined at 50° towards N50°. The thickness of the overburden is high ranging from 20 to 25 m. A debris kind of dry barren slope having overall fine-grained material with clayey silt was observed at this slope section. The inclination of the section is about 50°. The upper slope is sparsely

vegetated. A few bushes were observed on the upper slope section. It has been observed that the toe wall, constructed along the roadside, got damaged due to movement of the slope forming materials. The factor of safety values for completely dry condition and 25% groundwater conditions have been found to be greater than one, indicating that the site slope is stable. However, the slope is unstable when the groundwater condition is 50% for which the FOS value is 0.926 (Table 5) indicating that the heavy rainfall may result in the slope instability.

#### Soil slope section–L21S10

This soil slope is located at a distance of about 240 m from Dunali village towards Chamba. The road has been cut within the debris soil overburden. On an average the height of the cut slope ranges up to 12 m. Though it varies from 8 to 12 m. The thickness of the overburden is high ranging from 12 to 18 m. This slope consists of assorted debris material including fine material (clayey silt). The slope surface has barren and dry strata. The inclination of the upper slope is 30° towards N90°. The length of the slope is about 10 m along the road. Sparse vegetation with a few bushes and small trees has been observed on the upper slope at the site. The small rock fragments of slate which fell down along the road were also observed. The FOS value calculated for each chart is given in Table 5. It can be concluded that the slope was stable with FOS greater than one for selected groundwater conditions.

#### Soil slope section–L22S11

This soil slope is located near Gehra village along NH-154A. The road has been cut within the debris soil overburden. On an average the height of the cut slope ranges up to 11 m. Though it varies from 7 to 11 m. The thickness of the overburden is high ranging from 13 to 19 m. The rotational type of failure was observed on the barren and dry slope at the slope section–L22S11. A few rock fragments were identified on the slope surface, and along the roadside also. Upper slope supports thick vegetation in the form of bushes and trees. The slope is inclined at an angle 50° towards N105°. The inclination of the upper slope is about 10°–20°. The FOS's were found to be greater than 1 for each selected charts as given in Table 5 indicating the slope to be stable for these groundwater flow conditions.

#### Soil slope section–L23S12

This soil slope is located at Gehra village along NH-154A. The road has been cut within the debris soil overburden. On an average the height of the cut slope ranges up to 15 m. The thickness of the overburden is high ranging from 14 to 20 m.

The potential of circular failure was observed on the dry barren soil slope consisting of broken and weathered slate rock at the current site. The slope is supporting trees and bushes on the upper portion. The inclination of the slope is 60° towards N50°. The soil samples were collected from the slope section and examined in the laboratory for assessment of the slope stability using CFC. The slope material which fell down earlier was observed at the bottom of the slope along the roadside. The FOS value calculated for chart 2 and 3 was found to be less than one in case of 25% and 50% moisture conditions as given in (Table 5) making the site unstable for these groundwater conditions while the slope is just stable at 0% moisture.

#### Soil slope section–L28S13

This soil slope is located at about 4 km from Gehra village towards Bharmour along NH-154A. The road has been cut within the debris soil overburden. On an average the height of the cut slope ranges up to 29 m. Though it varies from 25 to 29 m. This is a barren dry slope with debris and assorted material. Upper slope supports thick vegetation in the form of bushes and trees. The slope is inclined at an angle 50° towards N330°. The inclination of the upper is about 15°–20°. When the slope is completely dry, the FOS value was observed to be greater than one indicating the slope to be stable, whereas the slope is unstable in the case of 25 and 50% saturation conditions as given in Table 5. This showed that the movement of the slope forming materials may take place during excessive rainfall.

## Conclusion

The other mitigation measures as suggested in case of slope section L1S1 were also suggested for the current slope." which is repeated eleven times; this should be avoided. One solution is the modification and reduction of the written text.

The detailed slope stability analysis of the 13 soil slopes is discussed in the present study. The detailed stability analysis of soil slope sections with thick soil/debris conditions, was performed using the circular failure chart (CFC) method. The outcomes of the CFC method showed that:

- Three soil slope sections, namely L2S2, L7S4, and L17S8 were unstable, with a FOS's less than 1 at completely dry conditions, while the remaining soil slope sections were stable at dry slope conditions.
- Six slope sections namely, L2S2, L7S4, L15S7, L17S8, L23S12, and L28S13 had FOS's less than one, and hence unstable and the remaining seven slopes were stable with their FOS greater than one at 25% moisture conditions.

- Only, two soil slope sites L21S10 and L22S11 were considered as safe with FOS's greater than one at 50% moisture condition while the remaining slopes are unsafe with FOS's less than one.

Based on the above outcomes, the possible solutions to avoid the slope stability problems along NH-154A are mentioned below:

The slope section L1S1, located near Chamba Township along NH-154A has a steep cut slope of 70°. The stability analysis indicated minimum FOS of 0.97 which indicates the slope is unstable, under such a condition, it is essential to provide stability measures for the cut slope taking the overall geometry of the slope as well as type of material. Re-profiling is an effective way of controlling slope instability in case of soil slopes; hence, it is suggested at 40° along with a bench of 3 m. A toe retaining wall has also been preferred along the toe of the slope.

The slope section L2S2, located just about the NHPC power house NH-154A has a cut slope inclined at 60°. The stability analysis indicated minimum FOS of 0.88–0.93, under such a condition, it is essential to provide stability measures for the cut slope taking the overall geometry of the slope as well as type of material. It is suggested to re-profile the slope at 50° with 2.5 m bench at the height of 9.5 m from the toe.

The slope section L4S3 is located at about 2 km distance from Rajera village towards Bharmour along NH-154A, is inclined at 50°. The stability analysis indicated minimum FOS of 0.91 which indicates the slope is unstable, under such a condition, it is essential to provide stability measures for the cut slope taking the overall geometry of the slope as well as type of material. Since the inclination of the slope is 50°, hence re-profiling of the slope is not needed at this section. However, a well designed toe retaining wall of height 5 m may be provided at the toe of the slope to protect the slope from future instability against rain and earthquake.

The soil slope L7S4 is located after crossing Kalsuin village towards Bharmour along NH-154A. The cut slope is nearly vertical (80°). The CFC method based analysis indicated FOS ranging from 0.9–0.96 which indicates the slope is unstable, under such a condition, it is essential to provide stability measures for the cut slope taking the overall geometry of the slope as well as type of material. It is suggested to re-profile the slope at 50° with 1 m bench in between.

The slope section L8S5, located near Rakh village along NH-154A is nearly vertical 80° towards N200°. The stability analysis using CFC showed minimum FOS of 0.98 which indicates the slope is unstable, under such a condition, it is essential to provide stability measures for the cut slope taking the overall geometry of the slope as well as type of material. It is suggested to re-profile the slope at 50° with 1 m bench in between.

The slope section L11S6, located nearby the Chamera power house at Mokhri village along NH-154A, is inclined at 50°. The stability analysis using CFC indicated minimum FOS of 0.94 which showed the slope is unstable, under such a condition, it is essential to provide stability measures for the cut slope taking the overall geometry of the slope as well as type of material. Since the inclination of the slope is 50°, hence re-profiling of the slope is not needed at this section.

This slope section L15S7 is located near Lothal village along NH-154A. The road has been cut within the debris soil overburden. The cut slope is inclined at 40°. Since the inclination of the slope is 40°, hence re-profiling of the slope is not needed at this section. However, a well designed toe retaining wall of height 10 m may be provided at the toe of the slope to protect the slope from future instability against rain and earthquake.

The slope section L17S8, located at 1 km distance from Dunali village towards Chamba along NH-154A, has a steep cut slope of 80°. The stability analysis indicated FOS ranging from 0.75 to 0.80 which showed the slope is unstable, under such a condition, it is essential to provide stability measures for the cut slope taking the overall geometry of the slope as well as type of material. It is suggested to re-profile the slope at 50° with two benches of 1 m at the height of 6 m and 12 m from toe.

The soil slope L20S9 is located at about 300 m before Dunali village towards Chamba along NH-154A is inclined at 50°. The stability analysis indicated minimum FOS of 0.93 which showed the slope is unstable, under such a condition, it is essential to provide stability measures for the cut slope taking the overall geometry of the slope as well as type of material. Though, the inclination of the slope is nearly 50°, but the loose strata is there at the slope surface in the form of overburden. Hence, the re-profiling of the slope section is suggested. The re-profiling may be performed at an angle of 40° with a single bench of 1 m at height of 10 m height from toe. A well-designed toe retaining wall of height 3–4 m may also be constructed at the toe of the slopes to provide support and protection to the slope from future instability due to rain and earthquake.

The slope section L21S10, located at distance of about 240 m from Dunali village towards Chamba along NH-154A has a cut slope of 50°. The stability analysis indicated FOS ranging from 1.04–1.15 which showed the slope is just stable. Though, the inclination of the slope is nearly 50°, but the loose strata is there at the slope surface in the form of overburden. Hence, the re-profiling of the slope section is suggested. The re-profiling may be performed at an angle of 40° with a single bench of 2 m at 6 m height from toe. A well-designed toe retaining wall of height 3–4 m may also be constructed.

The slope section L22S11, located near Gehra along NH-154A, has a cut slope of 40°. The stability analysis

indicated minimum FOS ranging from 1.29—1.43. Since the inclination of the slope is 40°, hence re-profiling of the slope is not needed at this section. However, a well designed toe retaining wall of height 3–4 m may be provided.

The slope section L2S12 located at Gehra village along NH-154A has a cut slope of 60°. The stability analysis indicated minimum FOS of 0.94 which showed the slope is unstable, under such a condition, it is essential to provide stability measures for the cut slope taking the overall geometry of the slope as well as type of material. It is suggested to re-profile the slope at 45° with 2 m bench in between.

The soil slope L2S13, located at about 4 km from Gehra village towards Bharmour along NH-154A has a cut slope of 50°. Since the inclination of the slope is 50°, hence re-profiling of the slope is not needed at this section. However, a well designed toe retaining wall of height 3–4 m may be provided.

The other mitigation measures were also suggested for slope section LIS1 viz. a polymer wire mesh shall be spread at the entire slope surface which shall be suitably stitched to the slope with the help of T-nails. This arrangement will help to reduce the erosion at the surface as well as to protect the materials to remain intact. It is also suggested to grow vegetation on the soil slope site. These precautionary measures were also suggested for slope sections L2S2, L4S3, L7S4, L8S5, L11S6, L15S7, L17S8, L20S9, L21S10, L23S12, and L28S3.

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## Declarations

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