



Landform Geometry for Restoration of Mountain Roads and Landslide Hazard Resilience

A. A. Virajh Dias, H. M. J. M. K. Herath, and L. K. N. S. Kulathilake

Abstract

Traveling on a mountainous road is attractive but questionable under aggressive climatic conditions such as extreme rainstorms. Roads are often designed in different geological complexity overlaying upper and lower terrains. The complexity of slope geometries, potential deformities, ground discontinuities, soil-rock composite nature, factors incorporated in structural integrity, the complexity associated with infrastructure developments, and unstable landform have long been causes of the increasing cost of road constructions in hills. In many instances, landform geometries and the natures of slope observed in-situ allow us to understand many salient features that we need to know in the design to mitigate landslide threats. The extent to which we make the collective effort to gather many features of landforms and their static representations concludes its validity. Findings are more forced to be based on geometrical evidence of slopes and cross-checked with an appropriate design criterion. A provision should describe a design or construction method that is deemed to comply with the site-specific conditions. Such an approach will save the enormous cost of investigations, design, and simplification for numerical evaluations, and also contribute to an indirect approach to road restoration and improve an appropriate approach for resilience to landslide hazards.

Keywords

Landform • Geometry • Roads • Slopes • Landslide • Rockfall

1 Introduction

A mountain road is the most connecting way of community in a low country with far the most beautiful cities of the hill country (Fig. 1) by allowing transportation for vehicles and pedestrians. A landform is the silent feature of the ground and can be a crucial element in understanding the difficulty of infrastructure developments in the mountains. In many instances, widening mountain roads often pose a challenge in avoiding potential landslide hazards, mainly due to various landform features of the upper and lower slopes (Fig. 1).

2 Geomorphological Evidences of Failure

Landslide is often considered as a downward and outward movement of earth-formed material on hill slopes. It is usually triggered under extreme rainfall or ground shaking (seismicity). Fortunately, no records of landslides occurring during the dry season or due to seismicity are found in Sri Lanka. Geomorphological pieces of evidence such as topography, geology, hydrology, slope, groundwater, and land use are considered to be intrinsic and extrinsic variables. In contrast, extrinsic variables are accounted for improper land-use practices, roads, infrastructure developments, and man-made activities. The landslide initiation can be explained as the slip initiation of the upper sliding surface due to the loss of resistance of earth mass, where acceleration occurs towards the downward slope, and deceleration occurs in a lower section. In addition, the spatial distribution of landslide geometry clearly integrates potential energy relief of soil, rock, water, vegetative species, and other spatial element spreading over the landslide boundary. Many observations of such large-scale landslides were recorded in Sri Lanka during the last two to three decades, and some of those are depicted in Figs. 2, 3, 4, 5, 6, and 7.

The Mulhalkelle landslide (1989), Gampalakadawala (2003), and Aranayake landslide (2017) were identified as

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Fig. 1 From Kandy travel along the Teldeniya road and Kandy-Mahiyangana-Padiyatalawa to completely travel along the 18 Bend Road. (Photo by Attractions Sri Lanka 2019)



Fig. 2 Traffic disrupted (trees and rock has fallen in to the road) on to the road at 6th bend area of the Kandy-Mahiyangana “18 hairpin road”, 20th January, 2020 (Photo by Hirunews.lk 2020)

large-scale landslides in terms of physical dimensions, numbers of victims, transported earth mass volumes, damage to infrastructures, relief efforts, failure patterns, and geological complexities. All those landslides seriously impacted many road networks and economic development due to being located in agroecological zones of Sri Lanka (Panabokke 1996). Observations indicate the start of a landslide as a de-stabilization of a vast mass of earth on the hillslope, which is subjected to the high water saturation that might trigger regolith sliding on the bedrock interface. It can induce substantial failure on the adjoining steeper downslope, including large rock fragments embedded in wet soil. The moving earth masses of the Mulhalkelle landslide (Fig. 3), Gampalakadawala landslide (Fig. 4), and the Aranyake Landslide (Fig. 5) contained highly saturated regolith material (unconsolidated, loose, heterogeneous superficial deposits covering soil and solid rock). It was noted that the rock-soil interface was saturated due to the propagation of the perched water table closer to the interface. Finally, the displaced material appears to have turned into a

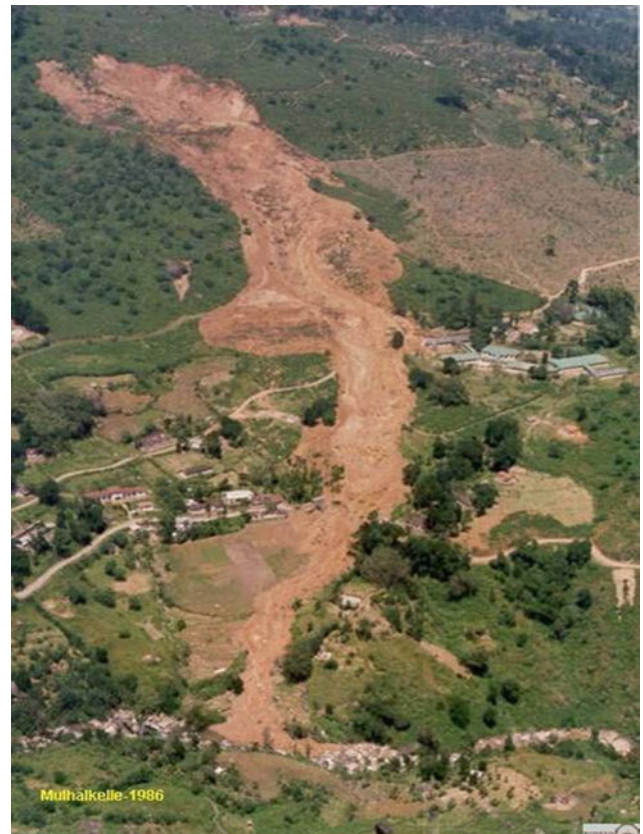


Fig. 3 This photo shows a stretch of a mountain slope destroyed by mudslide in Mulhalkelle, Nuwara Eliya district, 1986, NBRO Report (1988)



Fig. 4 Gampalakadawala Landslide (6 victims, Kalawana). Outburst floods resulted from mass movements temporarily blocking a “Delgoda Ganga” river at lower elevation, May, 2003

highly mobile flow, judging from damage to many elements at the lower elevation. The underlying geological structure of this area might be complex, jointed, highly foliated, and thus highly deformable structures. The rock surfaces visible



Fig. 5 Aranayake landslide in Sri Lanka is now thought to have killed about 122 people. The landslide was triggered by an exceptional rainfall associated with a slow-moving tropical cyclone, 2016. *Photo by Sri Lanka Red Cross*



Fig. 6 Sliding surface or the point of initiation of the Aranayake landslide in Sri Lanka, 2016 *Photo by Sri Lanka Red Cross (2016)*



Fig. 7 A landslide area at Kaluthara, 80 km from Colombo Sri Lanka on May 26, 2017, *Photo by The Straitstimes Asia (2017)*

on the remaining ridge have different inclinations from those exposed on the bedrock. Such geological complexities are usually difficult to explore before a landslide occurs. The mobile material appears to be weathered regolith interacting with a massive volume of groundwater during transportation of the earth material.

3 Study Background

This research aimed to develop a database of stable and unstable cut slopes (older than 20 years) through field verifications after heavy rainstorms recorded in the hilly/mountainous areas of Sri Lanka. The research started in late 2000 by implementing the “Pre-Feasibility Study for Designing Major Roads in Landslide Area” by the Central Engineering Consultancy Bureau (CECB 2000). The project was funded by the Japan International Cooperation Agency (JICA) through the Road Development Authority (RDA) of Sri Lanka. The activity was further studied under the IPL Certified Project ID-200, 2015, titled “An assessment of the rockfall susceptibility based on cut slopes adjacent to highways and railways,” implemented by the CECB. Subsequently, the study was carried out in 2003, 2006, 2008, 2012, 2016, and 2019. In addition, the CECB has been awarded the World Center of Excellence (WCoE) (Dias et al. 2017) for Landslide Risk Reduction under the theme of “Model Policy Framework, Standards and Guidelines” by the International Programme of Landslide (IPL) since 2014. The main objective of the study is investigating the design requirements of road cut slope stability along the (a) Ratnapura-Balangoda-Haputale highway, (b) Kandy-Gampola-Nuwara Eliya highway, and (c) Kandy- Hunnasgiriya-Madamaha Nuwara-Mahiyangana highway (See Fig. 8). Considering the ages of these highways, we realize that the non-engineered remedial designs adopted for the roads have stayed in balance with the road environments for 20 years or longer.

4 Landforms in Sri Lanka

Sri Lanka is characterized by a southern-central mountain range that rises to 2524 m above sea level at its peak (Erd., 1984). According to the various findings and documentation, the island consists of seven major landform units, viz. (i) coastal plain, (ii) continental shelf, (iii) circum-island peneplain, (iv) central massif, (v) Sabaragamuwa hills, (vi) Galoya hills and (vii) Elahera ridges (Erd.,1984).The entire area is covered by various landforms, from flat erosion



Fig. 8 Location map of the study and field verification survey locations. **a** Ratnapura-Balangoda-Haputale highway, **b** Kandy-Gampola-Nuwara Eliya highway and **c** Kandy- Hunnasgiriya-Madamaha Nuwara-Mahiyangana highway

or peneplain to a complex assemblage of mountains, ridges, plateaus, and valleys.

The mountainous landform is mainly due to geological and erosional history, which is considered one of the oldest and most stable parts of the earth's crust, namely Precambrian deposits in the Highland series (Cooray 1967). More than 90% of Sri Lanka is covered with highly crystalline, non-fossiliferous, Precambrian age, metamorphic rocks. These Precambrian rocks, which metamorphose under granulite facies and amphibolite facies, are subdivided into three groups based on lithology, structures, and ages of the rocks (Cooray 1984). Almost all hill country regions overlie highland series high grade, crystalline metamorphic rocks (Herath et al. 2014). The main rock types of this series are meta-sediments (quartzite, Marbles, garnet-sillimanite schists) and charnockite gneisses. Other rock types are biotite gneiss, hornblende-biotite gneiss and schists, and garnet-sillimanite gneiss (Cooray 1984).

5 Hydrological Records

In the late '80 s, when information was scarce, the landslide triggering rainfall threshold was placed at 200 mm in 72 h, provided rain in the area continued (Bhandari et al. 1992).

The above criterion did work partially; the probability of landslide occurrence as a rainfall intensity ratio spotlights the indicators that help assess the dynamic of rain-triggered

slope movements (Bhandari and Dias 1996). This study was conducted during the '90 s. The conditional probabilities were only examined partially in the case of reactivation of recent, seasonally active landslides. Rainfall records for the months of landslide events tell that 24 h rainfall associated with a landslide event was generally 2 to 23 times higher than the average daily rainfall (Bhandari and Dias 1996). The empirical rule is reasonably accurate if the average annual rainfall exceeds more than 3000 mm in the wet zone of the country.

The intense rainfall of 522 mm/day followed by a tropical storm on 15th May 2003 triggered 78 landslides in the Kalawana Division. Antecedent rainfalls during the ten days before the storm reached about 272 mm, increasing the soil moisture and causing soil surface erosion in various parts of Kalawana in the Ratnapura District. In November, the total three-day rainfall reached 656 mm and was the highest in 1947 (Dias and Gunathilaka 2014).

6 Landform Geometry and Mountainous Road Infrastructure

The mountainous slopes are predominantly convex-concave form and occasionally retain a planar slope segment within dipping slopes of in-situ rock. Dipping rock surfaces and many eroded rock slopes favor the development of various instabilities, and some lead to triggering significant landslides. Slope deformities and geometries initiate the natural degradation process of soil and rock, and history can be traced back millions of years (Fig. 9).

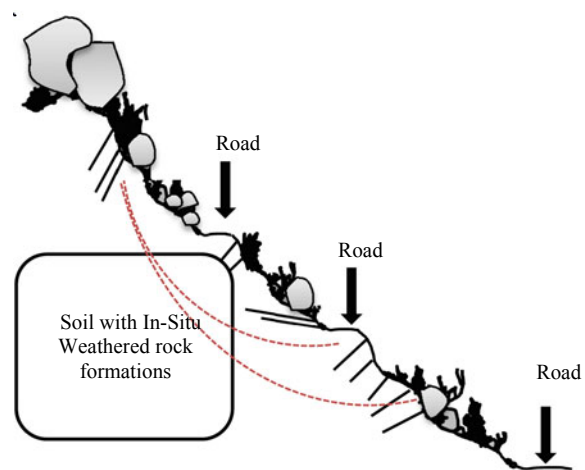


Fig. 9 Typical cross section of mountain hill slope

7 Data and Method of Approach

A total of 67 records were targeted for a detailed study out of 110 records of cuttings, bank failures, or landslides, as indicated in Table 1. The study is concerned with observations on the heights of failure, stable ground conditions, failure patterns, landforms, land uses, and geologies (Fig. 10).

7.1 Failure on Upper Slope Stability

The most common instabilities in roadside slopes mainly lie in immediate upper slope landform at which land-use practices were cultivation of economic crops (tea, vegetable), forestry, or home garden. The failure patterns are commonly associated with shallow rotational or translational failures

Table 1 Assessing potential stability according to the refined data

Point No.	Easting	Northing	Elevation MSL	Location	Type of failure	Slope angle	soil/rock type	Upper veg	h1/m	h2/m	Total H	toe wall	drain
POI 098	001-92-811	001-62-123	520	Kudawa, A4 Road	S	60.26	RS/HWR	HG	6.3	4.9	11.2	no	no
POI 103	001-95-434	002-64-209	569	Dambagahamada	S	63.43	SN	HG	4	–	4	no	yes
POI 104A	001-96-269	002-65-008	561	100 m away from Halgahawela (loc.10)	S	70.35	WR	HG	4	–	4	no	no
POI 113	001-98-399	001-67-353	563	Seelogama, A4 Road	S	74.05	RS/WR	HG	5	5	14	no	no
POI 115	001-98-999	001-67-802	557	Seelogama, A4 Road	S	63.43	MWR	HG	3	6	9	no	yes
POI 115A	001-98-999	001-67-802	557	Seelogama, A4 Road	S	74.05	MWR	HG	6	4	13	no	yes
POI 116	001-99-600	001-68-431	572	Belihuloya, A4 Road	S	66.8	MWR	HG	7	–	7	no	no
POI 119 A	001-99-600	001-68-431	572	Belihuloya, A4 Road	S	77.91	RS	FO	4.5	–	4.5	no	yes
POI 121	002-02-012	001-69-083	628	Pambahinna, A4Road	S	74.05	HWR	HG	5	–	5	no	no
POI 144	001-83-398	002-12-887	939	Pussellawa, A4Road	S	75.96	MWR/WR	TEA	4.5	5	9.5	no	no
POI 145A	001-84-234	002-12-875	976	Somagama, A4 Road	S	75.96	RS/WR	TEA	4	3	7	no	yes
POI 145C	001-84-234	002-12-875	976	Somagama, A4 Road	S	77.9	RS/WR	TEA	4	8	12	no	yes
POI 146	001-84-762	002-12-575	972	at Pssellawa Police Station	S	65.09	RS/HWR	HG	3.5	2.5	9	no	yes
POI 151	001-92-108	002-04-635	1271	Palagolla, A5 Road	S	77.9	HWR	HG	6	6	12	no	yes
POI 152	001-92-646	002-04-333	1379	Wedamulla	S	66.8	HWR	TEA	4.5	4.5	9	no	yes
POI092	00,191,834	00,161,429	541	Balangoda Bypass, AB7	S	75	RS	HG	4.0	–	4	no	yes
POI095	00,193,773	00,162,852	520	Imbulpe, A4 Road	S	59	HW/CWR	FO	8.7	7.1	15.8	no	yes
POI112	00,208,053	00,173,869	784	at 119 km post	S	58	CWR	FON	6.9	4.0	10.9	no	no
POI 099	001-93-222	002-62-014	519	Gammaduwa, Matale	F	57.26	RS/HWR	HG	6	–	6	no	no
POI 100	001-93-784	002-62-825	506	Gammaduwa, Matale	F	57.26	RS/HWR	HG	8	8	16	no	no
POI 101	001-93-729	001-63-376	513	Rathmalwinna	F	60.26	RS/HWR	HG	8	–	8	no	no
POI 102	001-95-253	002-64-205	550	Dambagahamada	F	66.8	HWR	HG	10	–	10	no	no
POI 104	001-96-269	002-65-008	561	Halgahawela	F	66.8	WR	HG	12	–	12	no	no
POI 105	001-97-107	001-66-090	481	Imbulpe, A4 Road	F	47.12	RS/WR	HG	7	–	7	no	no
POI 106	001-97-411	001-66-295	477	Imbulpe, A4 Road	F	70.35	WR	HG	8	–	8	no	yes
POI 107	001-97-605	001-66-409	512	Gilma-Imbulpe	F	60.26	RS/HWR	HG	7.2	2.5	9.7	no	yes
POI 107A	001-97-605	001-66-409	512	Gilma	F	63.43	HWR	HG	6.2	3	9.2	no	yes
POI 107B	001-97-605	001-66-409	512	Gilma	F	64.43	HWR	HG	6	3	9	no	yes
POI 108	001-97-638	001-66-510	513	Gilma	F	64.43	RS	HG	6.2	5	11.2	no	yes
POI 108A	001-97-638	001-66-510	513	about 50 m away	F	63.43	RS	HG	5.5	1.5	7	no	yes
POI 109	001-98-065	001-66-813	555	Imbulpe, A4 Road	F	77.91	RS/WR	HG	5	6	11	no	yes
POI 109A	001-98-065	001-66-813	555	Imbulpe, A4 Road	F	74.05	RS	HG	7	–	7	no	yes
POI 110	001-97-984	001-66-877	556	Imbulpe, A4 Road	F	60.26	RS/WR	HG	10	–	10	no	yes
POI 111	001-97-936	001-66-962	560	Imbulpe, A4 Road	F	63.43	HWR	HG	4.6	4.6	9.2	no	no

(continued)

Table 1 (continued)

Point No.	Easting	Northing	Elevation MSL	Location	Type of failure	Slope angle	soil/rock type	Upper veg	h1/m	h2/m	Total H	toe wall	drain
POI 112	001-98-093	002-67-115	565	Puwakgahawela old land slide	F	70.35	RS	FO	12	–	12	no	no
POI 114	001-98-452	001-67-478	558	Seelogama, A4 Road	F	60.26	RS/HWR	FO	12	–	12	no	yes
POI 115B	001-98-999	001-67-802	557	Seelogama, A4 Road	F	70.35	MWR	HG	6	5	15	no	yes
POI 118	002-00-221	001-68-818	613	Galagama, A4 Road	F	75.96	HWR/MWR	FO	4.5	–	4.5	no	yes
POI 118A	002-00-221	001-68-818	613	Galagama, A4 Road	F	79.88	HWR	FO	4.6	4.6	9.2	no	no
POI 118B	002-00-221	001-68-818	613	Galagama, A4 Road	F	75.96	HWR	FO	9	–	9	no	no
POI 119	002-00-466	001-68-615	634	Belihuloya, A4 Road	F	77.91	RS	FO	5	–	5	no	yes
POI 120	002-00-707	001-68-611	635	Belihuloya, A4 Road	F	77.91	WR	RF	6.5	–	6.5	no	no
POI 123	002-04-634	001-07-056	741	Dimbulgoda	F	60.25	WR	FO	6	6	12	no	yes
POI 124	002-04-954	001-70-226	758	Dimbulgoda	F	58.73	HWR	FO	8	6	16.5	no	no
POI 125 A	002-08-021	001-73-804	787	Kalupahana, A4 Road	F	63.43	RS	FO	5	4	14	no	no
POI 126	002-09-051	001-74-045	787	Sapugaha watta, Kalupahana—near the tunnel	F	63.43	RS/COL	HG	7	7	15	no	no
POI 128	002-13-981	001-73-672	973	Beragla, A4 Road	F	75.96	MWR	HG	7.5	4	11.5	no	no
POI 130	002-20-140	001-74-071	1400	Boralumankoda, A5 Road	F	80.67	WR	HG	3	11	14	no	no
POI 137	001-80-176	002-26-771	532	at 2 km post-Kandy Gampola road	F	75.96	RS/HWR	HG	5.5	2	7.5	no	yes
POI 138A	001-78-644	002-16-667	516	Boralumankada, Gampola—N'eliya road	F	79.87	RS	HG	4.5	6	10.5	no	no
POI 139	001-78-674	002-16-346	540	Ulapane, A5 Road	F	77.9	RS/HWR	HG	5	2	7	yes	no
POI 139A	001-78-674	002-16-346	540	Ulapane, A5 Road	F	77.9	RS/HWR	HG	3	3	6	yes	no
POI 140	001-79-956	002-14-552	595	Ulapane, A5 Road	F	70.35	RS/WR	HG	5	5	10	no	yes
POI 141	001-80-730	002-13-291	737	Ulapane, A5 Road	F	77.9	MWR	HG	2.6	2	4.6	no	no
POI 143	001-82-684	002-12-900	888	Udawalpala, A5 Road	F	77.9	RS/HWR	TEA	6	2	8	no	yes
POI 143A	001-82-684	002-12-900	888	Udawalpala, A5 Road	F	79.87	RS/HWR	TEA	3.5	–	3.5	no	no
POI 145	001-84-234	002-12-875	976	Pussellawa, A5 Road	F	75.96	RS/HWR	TEA	4	10	14	no	yes
POI 145B	001-84-234	002-12-875	976	Pussellawa, A5 Road, Near to KP 145	F	77.9	RS/WR	TEA	4	6	10	no	yes
POI 145D	001-84-234	002-12-875	976	Pussellawa, A5 Road, Near to KP 145	F	79.87	RS/WR	TEA	4	5	9	no	no
POI093	00,192,751	00,162,136	523	Balangoda, A4 Road	F	59	RS	HG	8.5		8.5	no	yes
POI094	00,192,946	00,162,157	511	Balangoda, A4 Road	F	75	RS/WR	HG	4.5		4.5	no	yes
POI096	00,195,268	00,164,219	553	at damaged house	F	45	HW/CWR	FO	10.0		10	no	no
POI100	00,198,069	00,166,812	550	Belihuloya, A4 Road	F	79	HWR	FO	6.2		6.2	no	yes
POI102	00,197,921	00,166,950	565	Belihuloya, A4 Road	F	79	CWR	FO	4.5	2.0	6.5	no	
POI105	00,200,267	00,168,785	635	near Bilihuloya	F	73	RS	FO	4.9	2.3	7.1	no	yes
POI109	00,200,717	00,168,634	640	Wellawaya, A4 Road	F	72	RS/CWR	FO	6.1		6.1	no	yes
POI110	00,200,746	00,168,679	640	abt 50 m frm POI 109 and 159 km post	F	67	RS/CWR	FON	7.8		7.8	no	no

F Fail, S Stable, RS Residual Soil, HWR Highly Weathered Rock, MWR Moderately Weathered Rock, WR Weathered Rock, CWR Completely weathered rock, COL Colluvium, FO Forest, HG Home Garden, FON Natural Forest reservation, TEA Tea, KP Kilometer post.

The overall location specific data was more than 110 locations and refined below according to most viable for design supportive road sections in mountain slope.

followed by a flowage mass. Observations revealed the fact that heavy rainfall events trigger failures (Fig. 11).

Weathered rock with upper slope de-stability

Soil layer contact with impermeable bedrock leads to increased pore water pressure at the interface of soil and

rock and ultimately causes a significant reduction of shear strength. The maximum permissible strain of soil material cannot withstand in-situ and leads to move downward and outward movement (see Figs. 12, 13 and 14).



Fig. 10 Upper and lower slope de-stabilization after construction of a road in mountain environment



Fig. 12 Failure observation of a road side slope cut section which was constructed at 0.5 to 3.5 m high without any retaining structures



Fig. 11 Immediate upper slope (slope section above the road) de-stabilization, Kalawana, Ratnapura, 2003

8 Evaluation of Landform Restoration Potential

The landslide is ‘almost all varieties of mass movements on slope including rockfalls, topples and debris flow sliding mass’ defined by Varnes 1984. The landslide body entrains a large volume of residual surface soil and then moves downstream along a gully to produce a debris flow disaster (Gao et al. 2017). The evaluation focused mainly on site-specific data collected during investigations, planning, designs, construction works, and widening of mountain roads. The number of road guidelines and specifications that describe site-specific design optimization of mountain roads is limited (Wyllie 1987). Therefore, experiences in understanding the process of slope degradation, refinements for site-specific issues, reactions to natural events, and historical records are critical tools

for understanding mountain road restoration works. The findings obtained through the study will create an appropriate environment for the decision-making process for roadway designs and mountain travels.

Some of the observations of the first-hand records were bound with geological evidence, landform patterns, land use, and improving the decision-making process towards reducing landslide vulnerability of roadway. Therefore, the following observations (see Figs. 15, 16, 17, and 18) are concluded as a decision-making tool for understanding observation-based approaches for assessing the potential stability based on the refined database of the study.

8.1 In-Situ Formed Weathered Rock or Completely Weathered Soil Form Geometries

Soil slopes fail differently, depending on the site settings (upper and lower slope stability), geometry, resistance to erosion, and other topographical factors. However, the numerical simulations have shown the collapse patterns, Type-a and Type-b in Figs. 15 and 16 are less likely to occur. And resistance to collapse is mainly governed by the unsaturated soil parameters. However, any prolonged heavy rainstorms will saturate the soil surface. In such instances, shallow slope failures are significant (Russel et al. 2008). According to the site records, a relatively low-cost, eco-friendly remedial design will help enhance the slope stability.

8.2 De-Stabilized Soil, Colluvium or Rock-Soil Complex Form of Geological Sections

Type-c and Type-d geometries (Figs.17 and 18) usually contain complex forms of stability. Many uncertainties are



Fig. 13 Example of rock formed failures along the road side slope. Wedge failure, translational slides and falling rocks are very much significant along the road sides. High hazard potential zone can be observed due to foliated and jointed rock formations



Fig. 14 Some stable landforms were also noticed during investigations. Highly to completely weathered rock surfaces consist of unsaturated soils, each having different visual and physical characteristics. Surface erosional potential is high if the weathered surface

contains any soluble minerals of metamorphic rocks. Usually, those sections stay stable for 20–40 years or more with minor surface improvements

among site-specific observations. The movements of rocks and rock-soil composites are two different modes of failure under those circumstances. Falling, rolling, bouncing, and sliding of rock are major sequences of de-stabilizing mechanisms (Brawner et al. 1975 and 1994) of failure related to the above. Therefore, a detailed study on geometries, energy, and simulations in different scenarios will conclude the appropriate remedial designs.

9 Statistical Interpretation of Data

Landform geometrical features coupled with mountain road restoration works for enhancing landslide hazard resilience were further interpreted through a statistically determined

approach. Many site-specific construction works are relatively old, more than 20–30 years at the data collection, and the research has continued since 2000. The historical data usage approach mainly focused on observations of weather-associated consequences as a tool for understanding roadside slope stability potential. The statistical interpretation primarily focused on understanding the way to reduce the cost of landslide remediation work and, thus, the appropriate roadway design on a mountain slope. The landform is a feature on the terrain's surface, which is further subdivided based on land use. We interpreted the collapsed and intact slope landforms in terms of land use, slope angle, slope height, and slope azimuth, as shown in Figs. 19, 20, and 21.

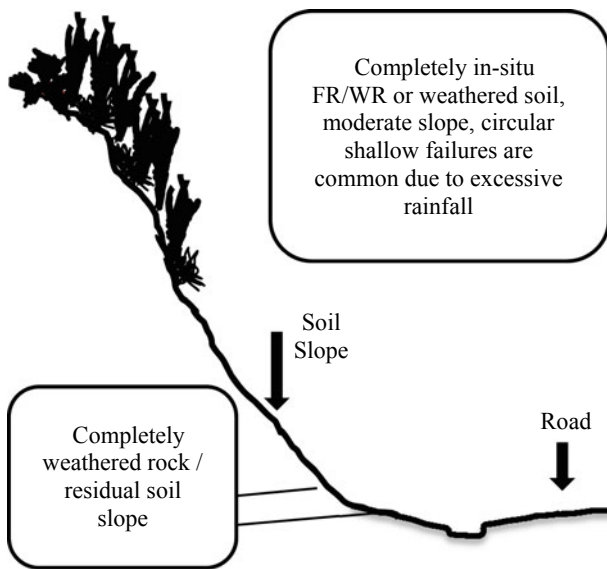


Fig. 15 Type-a: No rocks/rock outcrop at the upper slope, lower slope is stable or failed with in-situ residual soil formations. Limited or less potential threat of slope failures

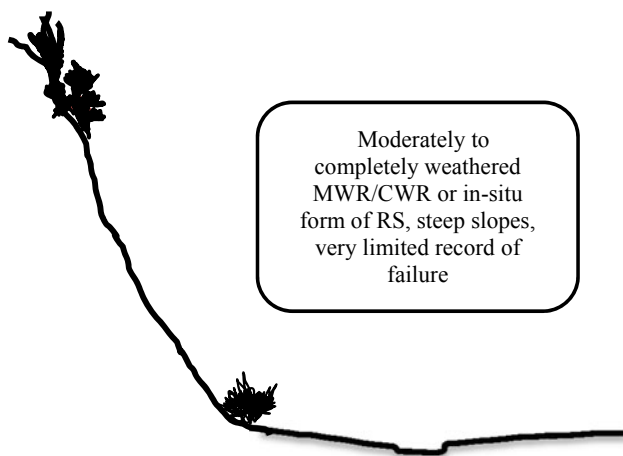


Fig. 16 Type-b: In-situ formed soil or completely weathered rock, less tendency or less potential slope failure according to field evidences

An illustrative example of the landform interpretation (Fig. 22) highlights the importance of studies on landform geometry of mountain road restoration. The studies significantly optimize the cost of total slope remedial measures against slope degradation in mountain road construction. Though observations were limited to 67 case histories, more data will support more corrective decisions during road designs.

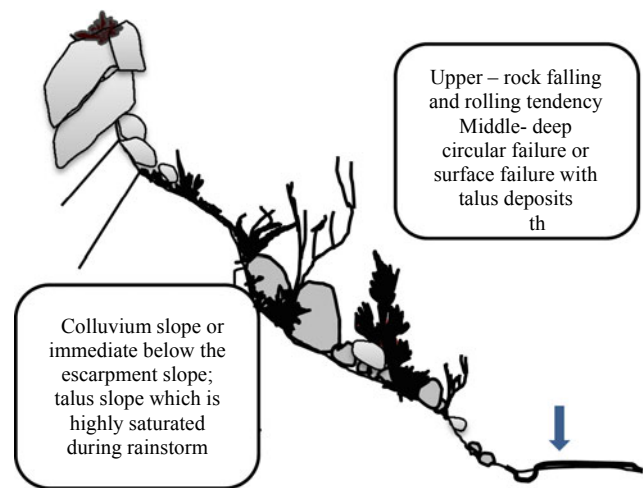


Fig. 17 Type-c: Rock falling, bouncing and rolling tendency of escarpment slope segments. Highly potential failure records at road side slope

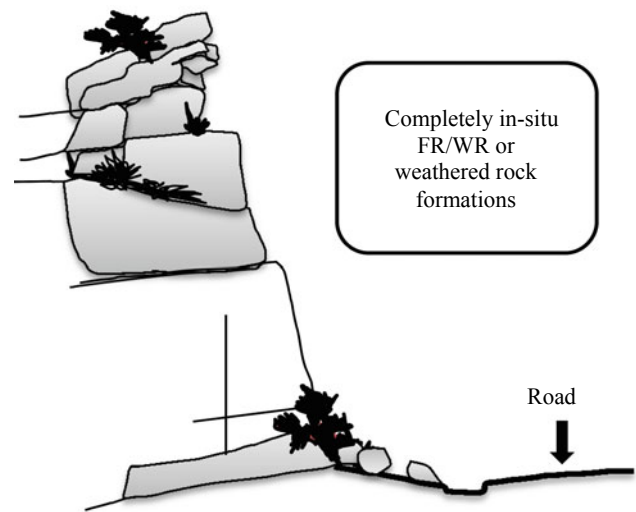


Fig. 18 Type-d: Completely rock slope, moderately to highly jointed/foliated rock face; Limited failure records, but highly potential rock falling, bouncing and rolling

10 Conclusion

Spatial interpretation and a case study

Hilly terrains in Sri Lanka, belonging to the humid weather pattern caused by global climate change, are wet and deserve attention in planning, designing, constructing, and maintaining mountain roads. Unsaturated residual soil

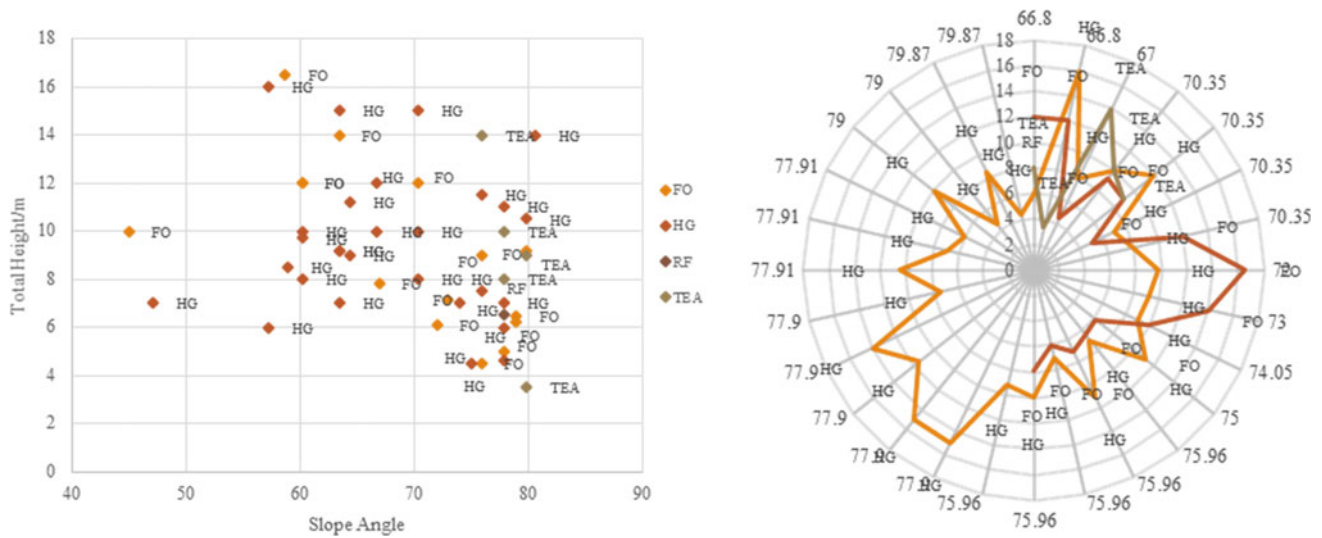


Fig. 19 Unstable slope records of stability plots for Slope Angle vs Total Height of earth cutting against to Land use above the road/upper slope segment (FO-Forest, HG-Home Garden, RF-Reforestation, and TEA-tea plantation). Height below 3.2 m is stable

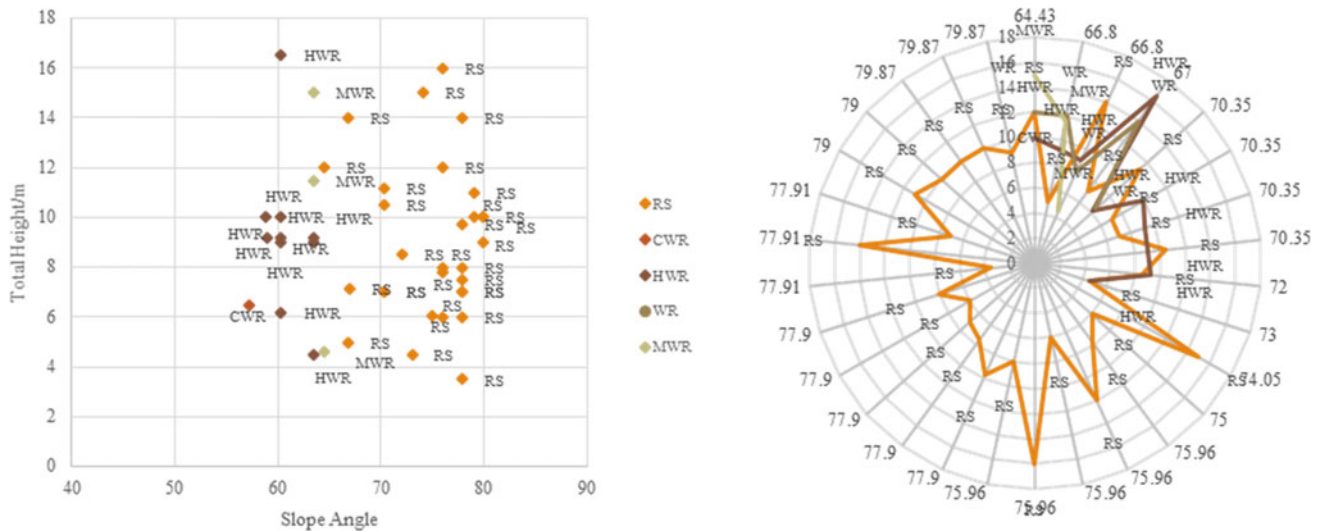


Fig. 20 Unstable slope records of stability plots for Slope Angle vs Total Height of earth cutting against Geology (ie. highly to completely weathered rock; HWR, MWR, CWR and residual soil condition; RS). Cutting Height below 4.6 m is stable

formations often cover these areas, indirectly contributing to high values of apparent cohesion during the non-saturated condition. Slopes of completely weathered soils (including highly weathered rocks) retain themselves in place due to the unsaturated behavior of soils, as shown in Fig. 21. Therefore, many cut-slopes of height not exceeding 3.2 m are potentially stable or can be restored with the least cost of remedial measures.

Land use in the upper slope significantly contributes to soil restoration potential. The geological complexity of cut

slope sections always needs to be toughly studied with an appropriate guideline of site-specific design.

The results of the study are summarized as follows.

- I. The complexity of slope geometries, potential deformities, ground discontinuities, and soil-rock composite nature are compulsory elements to understand and dominant parameters to describe the on-site stability of earth cut slope.
- II. Cut slopes of roads are often designed in different geological complexity overlaying upper and lower

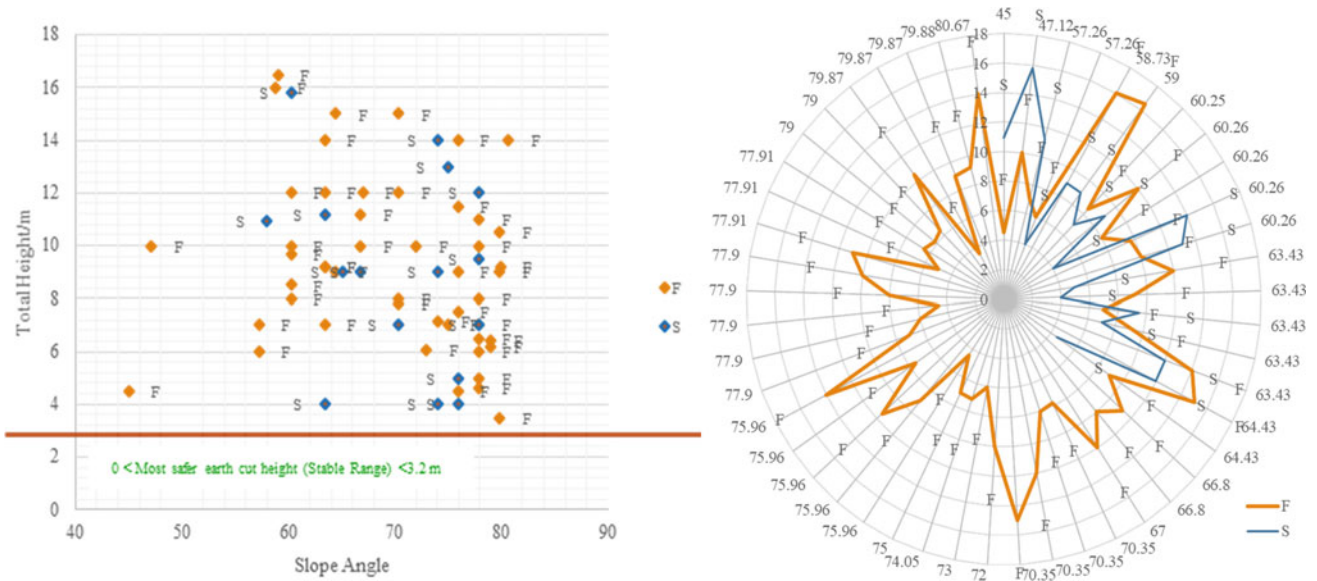


Fig. 21 Decision making stability plots for Slope Angle versus Total Height of Earth cut; Each point data contains different visual and physical characteristics including geology (highly to completely weathered rock, land surfaces), multiple landforms, stability criteria, failure-F and stable-S. Study concludes height below 3.2 m is stable even under different geological conditions or land use

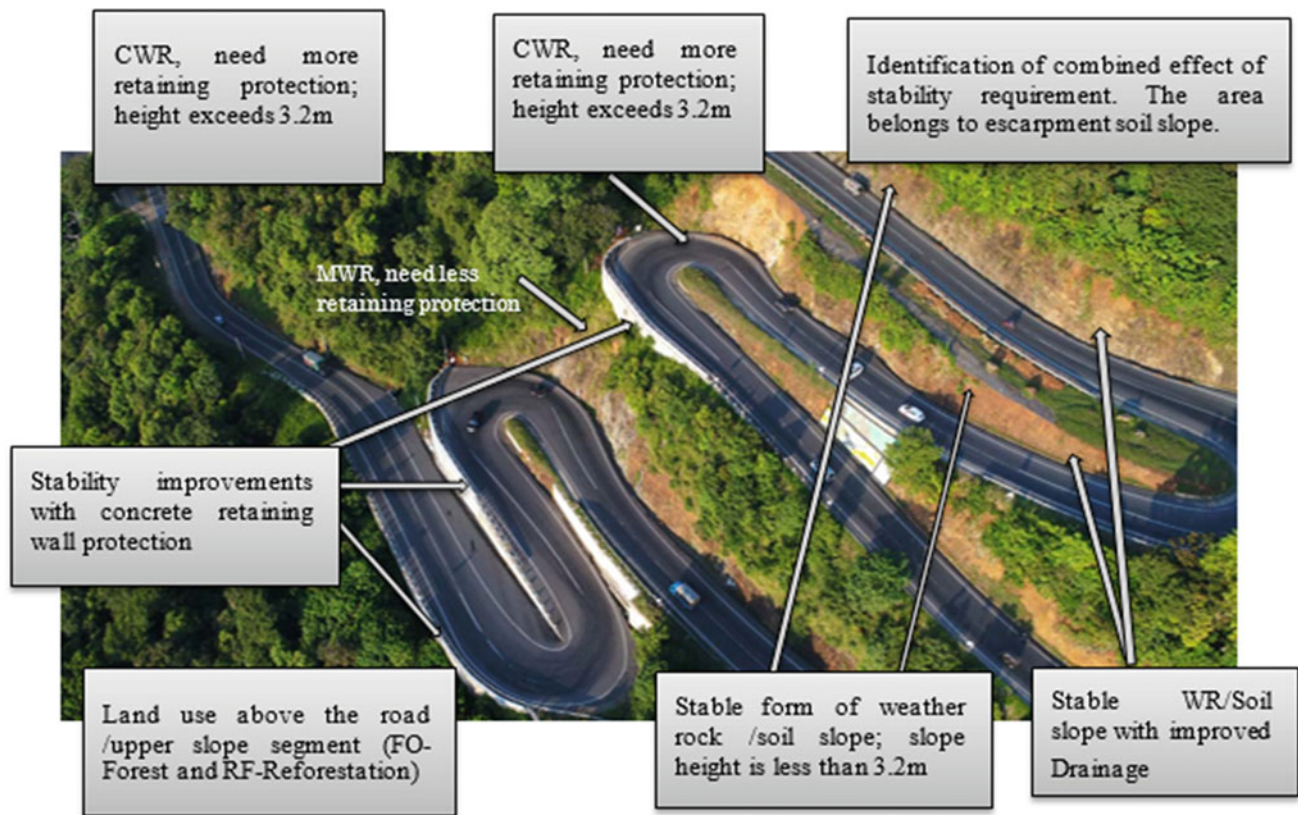


Fig. 22 Mountain slope stability measures adopted in “18 Hairpin Bend” Kandy-Mahiyangana highway (Photo by <https://www.mapakadavillage.lk/En/five-facets-about-mahiyangana/>), Sri Lanka

landforms. Therefore, accurate interpretation of those data is essential.

- III. Understanding factors incorporated in geo-structural integrity and potentially unstable landform are the key elements that decrease the cost of remedial measures on hill slopes.
- IV. In many instances, designing a wider section of mountain road is often challenging given landslide potential due to various landform features of upper and lower slopes.

Investigating and analyzing the soil properties and parameters that affect the stability of residual soil slope against all road cutting sections are usually expensive and time-consuming.

The above finding and approach allowed for site-specific generalization. Therefore, it is advisable to use additional criteria to predict the stability potential of cut slopes in road designs. More information about the cut slopes of mountain roads is required for more reliable prediction or design optimization.

More research on the road cut slope protections, data gathering of constructed slopes, data evaluation, and design of remedial measures will be recommended for very mountain regions/countries deep in mountains. They ultimately contribute to the development of landslide hazard resilience.

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