Preliminary investigation on Cyclone Remal-induced landslides in Aizawl, Mizoram, Northeast India, on the 28th of May 2024

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Preliminary investigation on Cyclone Remal-induced landslides in Aizawl, Mizoram, Northeast India, on the 28th of May 2024

Abstract On the 28th of May 2024, Cyclone Remal brought intense rainfall, triggering catastrophic landslides in Aizawl, the state capital of Mizoram, northeast India. The region is prone to landslides due to its fragile geology and steep terrain, and it has experienced severe damage, including loss of life, destruction of property, and disruptions to essential services. It had a severe impact on society, resulting in 34 fatalities with 33 bodies recovered and affecting 72 families, leading to the evacuation of 54 houses within Aizawl. It also affected the cemeteries of four localities. Among the numerous landslides observed during the field survey, fourteen sites were selected for the study. This study aims to assess the social impacts of these landslides and analyze the failure mechanism involved to guide future disaster preparedness and mitigation strategies. In addition to the information gathered from the government and social media, a field-based method of investigation was used in this study. The methods involve site visits, interviews with local communities, and an analysis of geological, geotechnical, and rainfall data. Geotechnical investigations were conducted at nine sites of the studied areas, all involving rock slides. An investigation was done into the stability of the affected rock slopes, including kinematic analysis, uniaxial compressive strength test (UCS), rock mass rating (RMR), continuous slope mass rating (CoSMR), and slake durability test. The field survey and interviews determined that the landslides caused 25 fatalities, with ten houses and twenty-two vehicles damaged in the Melthum and Hlimen areas. The total property loss was estimated to be Rs.3.4 crores. Landslides displaced more than 300 graves. Most of the probable slope failure observed using kinematic analysis show planar and wedge types of sliding. The studied rock mass of the slope falls under the poor to fair class in RMR ratings and ranges from partially stable to completely unstable in the CoSMR assessment. The rock collected from nine locations of the study landslide area shows medium to high durability and a strength of 14.8 to 22.6 MPa using slake durability and uniaxial compressive strength test (UCS), respectively. The study concludes that while intense rainfall was the primary cause, contributing factors like lack of expert consultation on slope modifications, weak rock mass characteristics, steep slopes, inadequate infrastructure planning, and fragile geological conditions increased the likelihood of slope failure. It seriously impacts society, resulting in many lives and infrastructure loss, economic hardship, and psychological stress, especially among those living in landslide areas. The findings emphasize the necessity of comprehensive land-use planning, improved infrastructure resilience, and coordinated disaster preparedness efforts to mitigate the risk of future landslides.

Keywords Wedge failure · Translational landslide · Aizawl · Cyclone Remal

Introduction

The first cyclonic storm of 2024, called "Cyclone Remal," made landed between Khepupara in Bangladesh and Sagar Island in West Bengal on the 26th of May 2024. On the 27th of May, the storm reached Northeast India, bringing relentless rainfall of 205 mm from the 27th of May 2024 at 8:30 am (Indian Standard Time) to the 28th of May at 8:30 am (Indian Standard Time) (data source: Directorate of Science and Technology, Mizoram State Meteorological Centre, Aizawl) that intensified throughout the night. By the morning of the 28th of May, around 6:30 am (IST), this escalating rainfall triggered catastrophic landslides across Mizoram, resulting in fatalities and extensive damages. The state government of Mizoram ordered the closure of all schools and offices on the 28th of May due to Cyclone Remal, except for essential services. The impact on society was profound, with the capital city of Aizawl particularly affected during this cyclone period. In total, there were 34 fatalities in Aizawl due to landslide, out of which 33 bodies were recovered and one unrecovered after the call off for the search and rescue operation. The water level in the Tlawng River, the primary source of water supply for Aizawl, reached its highest level in history, eventually destroying the water pumping system of the Department of Public Health Engineering (PHE), the government of Mizoram. The pumping machines GAWSS I and GAWSS II were damaged and non-functional due to a landslide. Numerous pipelines within the city were also damaged, causing water supply problems throughout the City (DI&PR 2024c). In addition, 10 Power Substations supplying 33 feeders were damaged within Aizawl, affecting over 60 localities without power supply (DI&PR 2024d). Among the landslides in Aizawl, 14 landslide sites were selected for detailed studies. The field survey in the selected study area showed that 10 Residential houses and 22 vehicles had been destroyed. Fifty-four houses were evacuated and transferred to the duly constructed rehabilitation center by the state government of Mizoram in the safe zones due to possible landslides in Aizawl (DI&PR 2024a). Four cemetery areas were significantly impacted by landslides, resulting in the displacement of over 300 graves in total. The residential buildings constructed under the Basic Service to Urban Poor (BSUP) scheme in Durtlang were at risk due to debris flow in the lower section of the complex. The state's Chief Minister of Mizoram has declared a State Disaster Relief Fund (SDRF) of Rs. 15 crores and an exgratia of Rs. 4 lakhs for each

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deceased (DI&PR 2024b). The present investigations aim to assess the stability conditions and causes of the landslides triggered by Cyclone Remal in Mizoram on the 28th of May 2024, focusing on the impact on society and identifying the triggering factors. The findings are intended to suggest future mitigation strategies to enhance resilience against similar natural disasters in Mizoram.

Study area

The study area is located in Aizawl City, the state capital of Mizoram, northeast India, which is bounded by Myanmar and Bangladesh to the east, south, and west, respectively (Fig. 1). The capital city of Aizawl is situated within the Indo-Burma subduction region, which is under seismic zone V (BIS 2002). The region tectonically deformed into high slope angles with extensive fracturing in the rock formations, which recently experienced significant seismic activity like an earthquake swarm in 2020 (Bharali et al. 2021). The study area is situated within the geological context of the Bhuban Formation, a part of the Surma Group, and belongs to the Miocene-Oligocene age. The fragile sedimentary terrain of the region, as a whole, is comprised primarily of highly inclined sandstone, shale, and siltstone (Ganju 1975), which experiences numerous landslides and rockfalls during the monsoon season. The geology, elevation, slope angle, and slope aspect of Aizawl City are illustrated in Fig. 2 a, b, c, and d, respectively. Aizawl has experienced devastating subsidence, landslides, and rockslides throughout history. On the 9th of August 1992, the landslides at Hlimen Quarry claimed more than 70 lives and destroyed 17 houses. Another tragic event occurred on the 11th of May 2013, when a rockslide at Laipuitlang claimed 17 lives and destroyed 15 houses (Dinpuia et al. 2014).On the 28th of May 2024, landslides occurred in various regions of Aizawl due to Cyclone Remal (Fig. 3). Among these, fourteen landslide sites with significant social impacts were selected for the study. Of the 14 selected sites, one is a debris flow located near BSUP Durtlang, and four are cemeteries with a thick accumulation of sediments. The remaining nine sites are rock slopes, where geological and geotechnical investigations were carried out.

Investigation on landslides

Field investigation and interview

To understand the impact on society, we conducted field surveys and interviews after the landslide incident among the affected families and local council members to assess property damage and human casualties. In addition to this, the study team has visited several vulnerable areas with the assistance of local authorities, offering immediate assistance by identifying hazardous zones and providing guidance on risk mitigation strategies. Awareness was held among the local people, helping them recognize potential threats and take proactive measures. The locations of landslides were marked using a handheld Global Positioning System (GPS). Unmanned Aerial Vehicle (UAV), Freeman's pro-L60 laser distance meter, and measuring tape were used to determine the dimension of the study area. Of the numerous observed landslides triggered by Cyclone Remal, 14 landslides having a significant social impact on society were identified. Among the 14 study areas, geotechnical studies were conducted at nine rock slide sites to determine the stability and failure mechanism. Photos of landslides and property damage in several locations of NH-54, Hlimen, and Methum have been taken (Fig. 4 a to q). Landslides in BSUP Durtlang and the cemetery areas of I.T.I, Kanan, Republic, and Kulikawn localities were studied based on field investigation.

Kinematic analysis was done to identify the possible modes of rock slope failure based on Markland's test (Hoek and Bray 1981) using DIPS 6.0 (Rocscience Inc.2010). The dip and dip direction of the joints were measured using a Brunton compass and plotted on a stereonet to analyze their relationship with the slope orientation, which is then utilized in CoSMR. Rock mass rating (RMR) (Bieniawski 1979) and continuous slope mass rating (CoSMR) (Tomas et al. 2007) were performed in nine locations, namely Melthum Landslide, Hlimen Landslide-1, Hlimen Landslide-2, and multiple sections of NH-54 (a–f), a section from Aizawl to Hualnghohmun. The five parameters of RMR were evaluated to calculate the basic RMR_b ratings. The volumetric joint count method (Jv) was used to determine rock quality designation (RQD) (Palmstrom 1982). The uniaxial compressive strength (UCS) of the rock was determined using the uniaxial compressive strength test apparatus. The RMR_b value calculated for the nine locations is given in Table 1. CoSMR is a modification of the slope mass rating (SMR) method, which is a continuous function, and the evaluation equation is the same as SMR (Eq. (1)) (Tomas et al.2007). The difference is in the computation of adjustment factors (F_1, F_2, and F_3), and the factor F_4 will be the same as in SMR. The ratings based on CoSMR are given in Table 2.

$$SMR = RMR_b + F_1 * F_2 * F_3 + F_4 \tag{1}$$

The adjustment factors F_1, F_2 *and* F_3 for CoSMR is calculated as (Eqs. (2)–(5))

$$F_1 = \frac{16}{25} - \frac{3}{500} arctan\left\{\frac{1}{10}(|A| - 17)\right\} \tag{2}$$

$$F_2 = \frac{9}{16} + \frac{1}{195} arctan\left(\frac{17}{100}(B - 5)\right) \tag{3}$$

$$F_3 = -30 + \frac{1}{3}\arctan(C)(Wedge\ and\ planer\ failure) \tag{4}$$

$$F_3 = -13 - \frac{1}{7}\arctan(C - 120)(Toppling\ failure) \tag{5}$$

where A represents the angle of parallelism between the slope dip direction and the discontinuity dip direction, for wedge failures, it is defined as the angle between the plunge direction of the intersection line formed by two discontinuities and the slope dip direction. Parameter B corresponds to the dip of the discontinuity for planar and toppling failures, while wedge failures refer to the plunge of the intersection line. C describes the dip relationship between the slope and the discontinuity.

Laboratory analysis

Rock samples were collected from nine locations, Melthum, Hlimen Landslide-1, Hlimen Landslide-2, and NH-54 (section a–f) to determine the rate of weathering and uniaxial compressive strength (UCS) following BIS (1981) and BIS (1979), respectively. Five tests

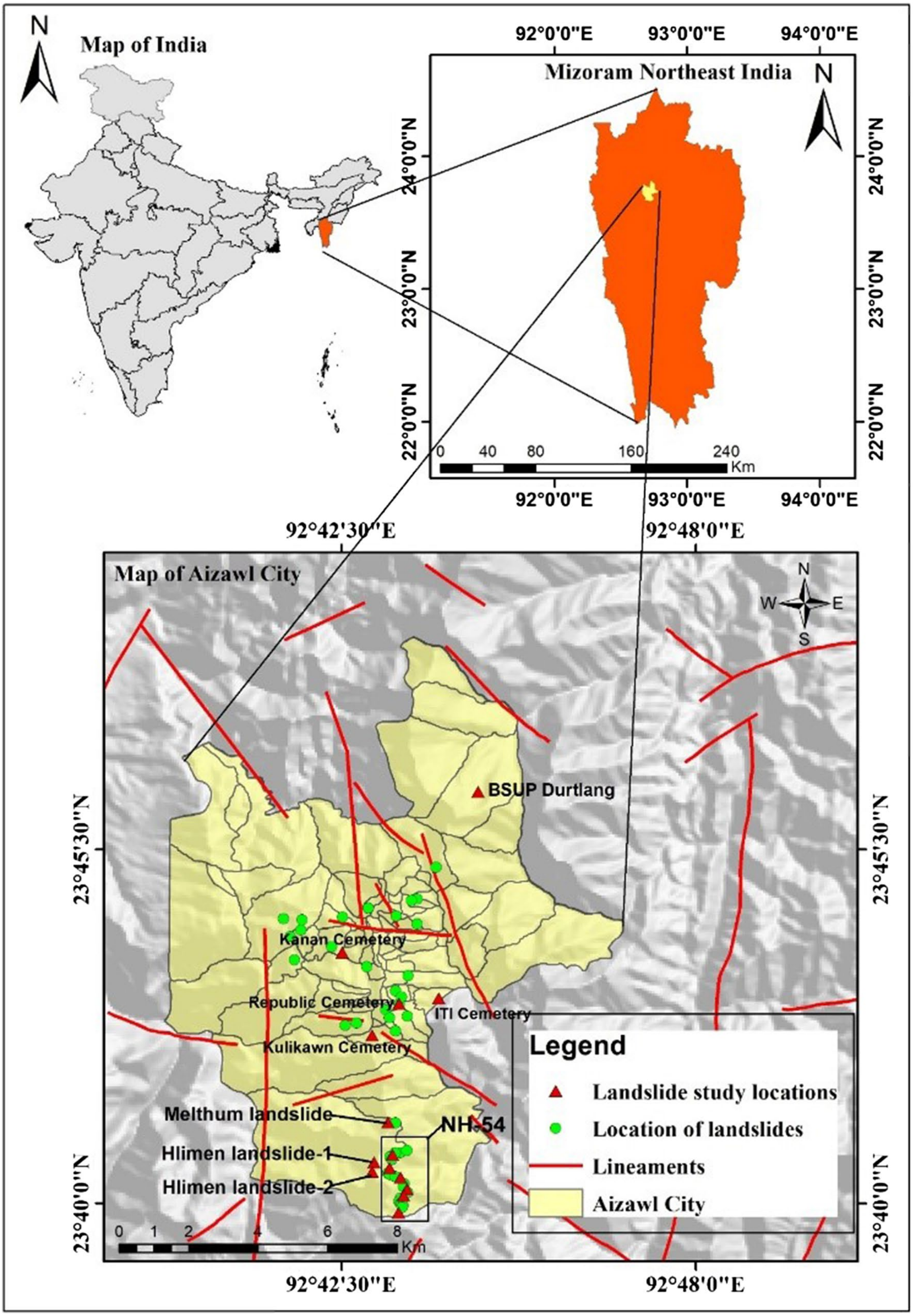


Fig. 1 Map showing the geographical location of Mizoram northeast India and the study area Aizawl city. Minor landslides in Aizawl are marked by green solid circle and the selected study landslide locations are marked by red triangles

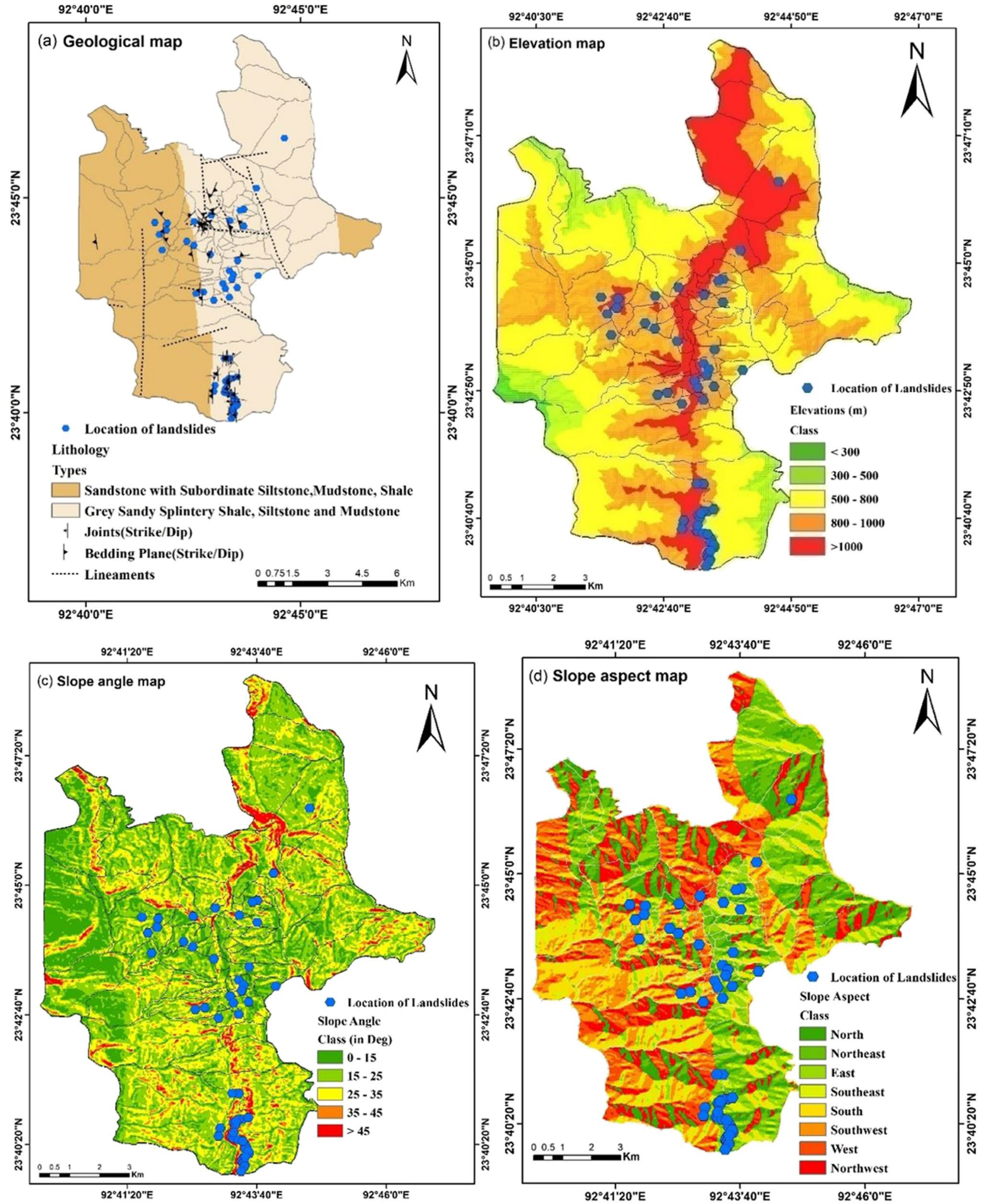


Fig. 2 Map of Aizawl generated using NASA SRTM (2013). **a** Geological map of Aizawl with lithology and lineaments (Geological Survey of India), locations of landslide, bedding, and joints attitude taken during field investigation. **b** Elevation map of Aizawl highlighting the location of landslides. **c** Aizawl slope angle map with locations of the landslide. **d** Aizawl map showing slope aspect and locations of landslide

Fig. 3 Random pictures of landslide damages in and around Aizawl. **a, b** Damage and displacement of houses caused by debris flow. **c**, **d** Road blocked and displacements of electric poles and wires due to collapse retaining wall

were conducted for each sample to obtain the specimen's UCS value. The values of durability and UCS are given in Table 3.

Rainfall data

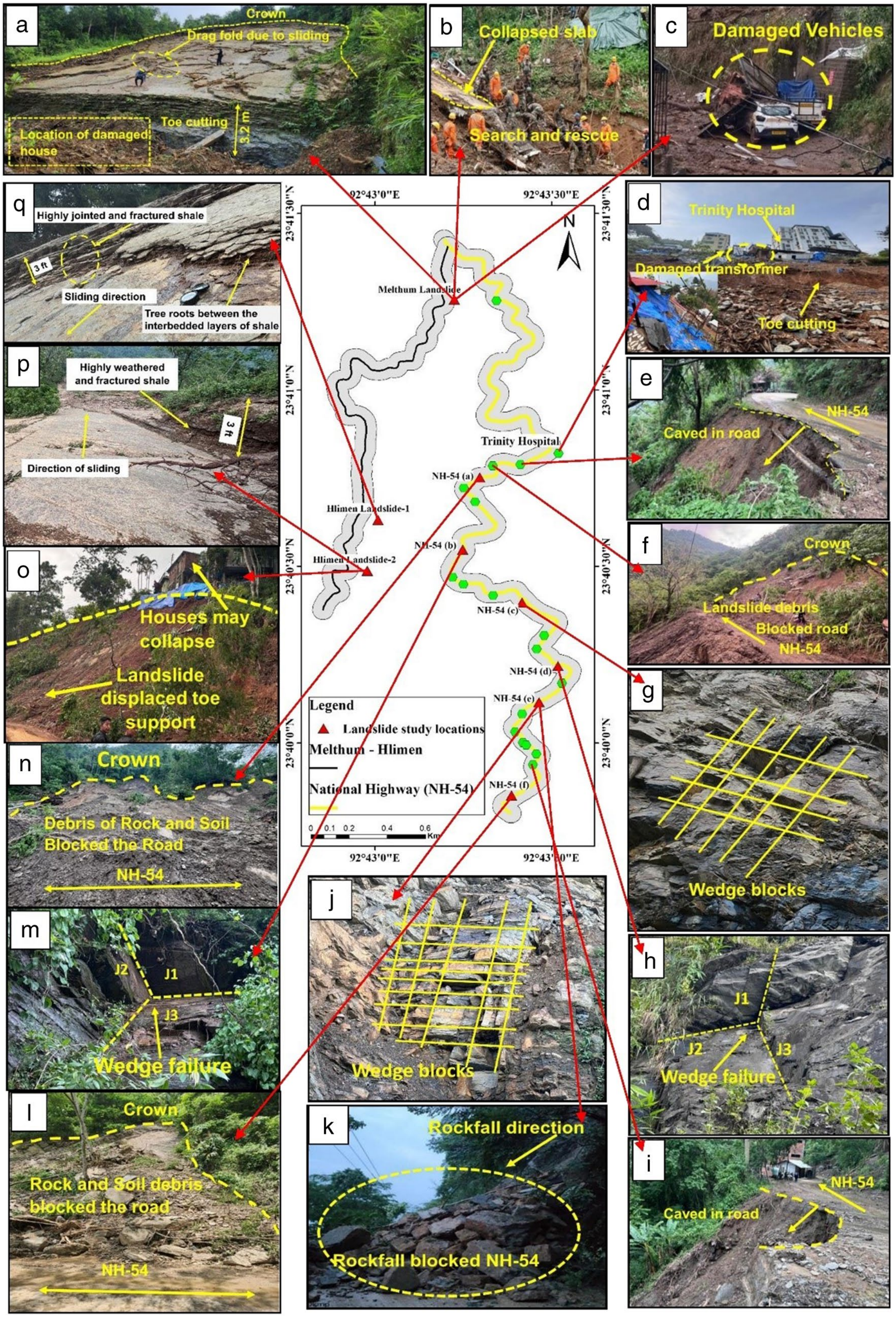
Daily rainfall data from January to September 2024 was obtained from the Directorate of Science & Technology State Meteorological Centre, the Government of Mizoram. Rainfall measurements were recorded using rain gauges located within Aizawl city, namely at Mizoram University (23°44′05″N, 92°39′57″E), College Veng (23°43′29″N, 92°43′35″E), Khatla (23°43′35″N, 92°42′12″E), Hlimen (23°40′17″N, 92°42′40″E), and Thuampui (23°44′41″N, 92°44′12″E). Figure 5 illustrates the cumulative rainfall curve for this period. Rainfall reached 205 mm on 28th May, coinciding with multiple landslides around 6:30 am in various locations of Aizawl. Leading up to the rainfall event that triggered the landslides, continuous rainfall began on the 24th of May and continued through the 25th, 26th, and 27th, peaking on the 28th May with recorded precipitation amounts of 2.2 mm, 8.2 mm, 21.8 mm, 80 mm, and 205 mm respectively (Fig. 6).

Results and discussion

The Aizawl Municipal Corporation has been enforcing Site Development and Slope Modification regulations since 2021, and a hazard map prepared by Geohazard International is used. The hazard map divides Aizawl into low, moderate, high, and very high zones based on the area's slope aspect, geology, and geomorphology. According to these regulations, any new construction must be preceded by a geotechnical investigation to ensure safety. The landslides in our study occurred predominantly in areas classified as high to very high-hazard zones (Fig. 7a). However, the large extent of these zones, covering approximately 85% of the area in Aizawl city, had made large-scale evacuation before Cyclone Remal logistically challenging. Instead, the focus was on enforcing the regulations to mitigate the landslide risks.

Melthum landslides

From the study, it was found that the most affected area due to the catastrophic landslide, which claimed 19 casualties, was located at Melthum (23°41′16.23″N,92°43′15.15″E). Search and rescue were


a
Crown
Drag fold due to sliding
Toe cutting
3.2 m
Location of damaged house
b
Collapsed slab
Search and rescue
c
Damaged Vehicles
d
Trinity Hospital
Damaged transformer
Toe cutting
e
Caved in road
NH-54
f
Crown
Landslide debris
Blocked road
NH-54
g
Wedge blocks
h
J1
J2
J3
Wedge failure
i
NH-54
Caved in road
j
Wedge blocks
k
Rockfall direction
Rockfall blocked NH-54
l
Crown
Rock and Soil debris blocked the road
NH-54
m
J2
J1
J3
Wedge failure
n
Crown
Debris of Rock and Soil Blocked the Road
NH-54
o
Houses may collapse
Landslide displaced toe support
p
Highly weathered and fractured shale
3 ft
Direction of sliding
q
Highly jointed and fractured shale
3 ft
Sliding direction
Tree roots between the interbedded layers of shale
92°43'0"E
92°43'30"E
23°41'30"N
23°41'0"N
23°40'30"N
23°40'0"N
N
Melthum Landslide
Trinity Hospital
NH-54 (a)
NH-54 (b)
NH-54 (c)
NH-54 (d)
NH-54 (e)
NH-54 (f)
Hlimen Landslide-1
Hlimen Landslide-2
Legend
Landslide study locations
Melthum - Hlimen
National Highway (NH-54)
0 0.1 0.2 0.4 0.6 Km

◂**Fig. 4** Landslide along Aizawl to Hualngohmun area. **a** Landslide at Melthum area. **b** The search and rescue at Melthum landslide. **c** Damaged vehicles due to rock slide in Melthum. **d** Landslide at Trinity Hospital damaged a transformer marked as a circle. **e** Caved in road along NH-54. **f** Landslide debris and mud flows in NH-54. **g** Wedge blocks observed in NH-54. **h** Wedge type failure in NH-54. **i** Caved in road at NH-54 **j** Wedge blocks observed in NH-54. **k** Debris of weathered shale and soil blocked the road **l** Rock and soil debris blocked NH-54. **m** Wedge failure observed in NH-54. **n** Debris of rock and soil in NH-54 blocking the road. **o** Landslide in Hlimen-2 showing the residential building at the crown. **p** Rock slide in Hlimen landslide-2 showing the direction of sliding, the thickness of overburden soil and highly fractured shale bed. **q** Rockslide in Hlimen landslide-1 showing the roots penetrating through the highly joint and fractured shale beds

jointly operated by the State Disaster Response Force (SDRF), the National Disaster Response Force (NDRF), and Non-Governmental Organisations (NGOs). The geology of the area constituted substantial bedrock of highly jointed and fractured sandstone overlain by a thin layer of shale about 1 m thick, capping the upper portion of the landslide scarp. The sliding area was recorded as 173 m in length and 30 m in width. The volume of displaced materials was estimated to be 5200 m^3. The average soil thickness in the area is 2 ft. Our investigations revealed that constructing a house at the top portion of the landslide (Fig. 7b right corner) was carried out illegally, disregarding AMC's regulations. The landslide debris and the building slide down the slope, destroying settlements and other residential structures and properties (Fig. 7b). Four residential buildings and ten vehicles damaged by the rockslide cost around Rs. 1.6 crores. This damage emphasizes the critical importance of a hazard map and the need for strict adherence to geotechnical investigations to prevent such disasters, serving as a crucial lesson learned from past events. Kinematic analysis suggests the potential for planar and wedge sliding in the Melthum area (Table 2). The RMR assessment shows a rating of 53 (Table 1), classifying the site as "fair." There is a probability failure of 0.4 to 0.9 in the CoSMR assessment, implying stability conditions from partially stable to completely unstable. The slake durability test gives a durability index value of 74.48% after the second cycle (Table 3).

Hlimen landslide-1

The landslide at Hlimen-1 (23°40′37.36″N, 92°43′2.38″E) measures a length of 216 m and a width of 72 m (Fig. 7c). It has been observed that the soil thickness above the layer ranges from 2 to 4 ft. The estimated landslide volume was 17,280 m^3. Tragically, six lives were lost, with six vehicles and two residential buildings completely damaged, and the nearby houses were evacuated due to the high risk of failure, as indicated by the red dotted lines in Fig. 7c. The total assessed value of the damaged property was approximately Rs.64.3 lakhs. It was observed that the current state of instability is metastable due to the presence of debris and vegetation on the way to failure along the slope. There is a probability of planar, wedge, and toppling failure with a maximum chance of planar failure. Based on the RMR value, the rock mass can be classified under the "fair" class (Table 1) and shows a probability failure of 0.4 to 0.9 under the CoSMR assessment (Table 2). Based on Franklin and Chandra 1972, the weathering durability of rock observed in Hlimen-2 can be classified as medium durability with a durability percentage of 74.27 (Table 3).

Hlimen landslide-2

In Hlimen landslide-2 (23°40′28.7″N, 92°43′0.19″E), houses were damaged with no casualties, and the nearby houses evacuated were marked circle in Fig. 7d.This landslide has a length of 213 m and a width of 67 m. The sliding volume was estimated to be 42,813 m^3. Four residential buildings and seven vehicles were destroyed. The total cost of damage in Hlimen landslide-2 is estimated at Rs. 1.17 crores. Groundwater seepage has been detected, and the thickness of the displaced shale bed measures 3 ft (Fig. 7d right corner). The possibility of planar and direct toppling failure was observed

Table 1 Rating of parameters for calculation of RMR (Bieniawski 1979)

Location No	Ratings						Rock mass class
	UCS	RQD	Joint spacing	Discontinuities	Groundwater	RMR_{basic}	
Melthum	2	8	8	25	10	53	Fair
Hlimen Landslide-1	2	8	10	25	10	55	Fair
Hlimen Landslide-2	2	3	10	25	10	50	Fair
NH-54 (a)	2	8	10	25	15	60	Fair
NH-54 (b)	2	3	8	25	10	48	Fair
NH-54 (c)	2	3	5	25	0	35	Poor
NH-54 (d)	2	8	8	25	15	58	Fair
NH-54 (e)	2	8	10	25	15	60	Fair
NH-54 (f)	2	8	10	25	15	60	Fair

Table 2 Stability class from continuous slope mass ratings

Location	RMR_{basic}	Failure	F1	F2	F3	F4	Ratings	Class	Probability of failure	Stability
Melthum Landslide	53	P	0.941	0.862	−59.53	0	4.71	V	0.9	Completely unstable
	53	W	0.954	0.847	−59.54	0	4.89	V	0.9	Completely unstable
	53	T	0.121	1	−6.57	0	52.21	III	0.4	Partially stable
Hlimen Landslide-1	55	P	0.799	0.83	−55.32	0	18.31	V	0.9	Completely unstable
	55	W	0.799	0.757	−57.28	0	20.35	V	0.9	Completely unstable
	55	T	0.119	1	−0.337	0	54.96	III	0.4	Partially stable
Hlimen Landslide-2	50	P	0.941	0.83	−55.32	0	6.79	V	0.9	Completely unstable
	50	W1	0.954	0.809	−1.73	0	48.66	III	0.9	Partially stable
	50	W2	0.246	0.684	−59.51	0	39.98	III	0.4	Partially stable
	50	T	0.12	1	−0.337	0	49.96	III	0.4	Partially stable
NH-54(a)	60	P	0.977	0.957	−58.41	0	5.38	V	0.9	Completely unstable
	60	W1	0.454	0.949	−58.72	0	34.7	IV	0.6	Unstable
	60	W2	0.149	0.163	−59.36	0	58.55	III	0.4	Partially stable
	60	T	0.12	1	−22.06	0	57.35	III	0.4	Partially stable
NH-54(b)	48	W	0.454	0.955	−58.53	0	22.62	IV	0.6	Unstable
NH-54(c)	35	W	0.454	0.83	−59.45	0	12.59	V	0.9	Completely unstable
NH-54(d)	58	W	0.707	0.991	−58.64	0	16.91	V	0.9	Completely unstable
NH-54(e)	60	P	0.707	0.987	−53.86	0	22.42	IV	0.6	Unstable
	60	W	0.707	0.983	−59.36	0	18.75	V	0.9	Completely unstable
	60	T	0.123	1	−0.771	0	59.91	III	0.4	Partially stable
NH-54(f)	60	P	0.954	0.984	−59.38	0	4.26	V	0.9	Completely unstable
	60	W	0.186	0.963	−59.58	0	49.33	III	0.4	Partially stable
	60	T	0.121	1	−24.69	0	57.01	III	0.4	Partially stable

(Table 2), and the area can be classified as "fair" with an RMR value of 50 (Table 1) and partially unstable to completely unstable with the probability of failure ranging from 0.4 to 0.9 based on CoSMR analysis (Table 2). The shale shows a durability index percentage of 74.22 and is classified as medium class, and the UCS value is 17.9 MPa (Table 3).

In the Melthum and Hlimen areas, it was found that the topographic slope and the bedrock share the same orientation, which read 36°/265° SW, facilitating planar failure. An incompetent layer of weathered, highly fractured shale around 8 cm thick is present within the entire stratigraphic formation. These layers are a potential failure plane when intense rainfall percolates into strata. Besides intense rainfall, the triggering factors include toe-cutting of bedrocks for the construction of RCC residential buildings, road constructions, weak geomechanical characteristics, and high slope degree (34° towards the West) with an adverse bedding relationship, which led to an oversaturation of the topsoil, which further intensified sliding of soil and shale layers at the soil-rock bed interface.

Aizawl to Hualngohmun landslides (National Highway NH-54)

About 32 landslide spots were identified along Aizawl to Hualngohmun, connecting Zoram Medical College, which falls under the National Highway (NH-54). Among these landslides, six sections (NH-54 a to f) were selected for detailed study (Fig. 1 represented in a red solid triangle inside a box of NH-54). All the landslides in this road section co-occurred on the morning of 28 May 2024. The estimated total area and volume of the landslides along this section were 7814 m^2 and 11,983m^3, respectively. The immediate effect of the landslide near Trinity Hospital was the displacement of the Power Transformer feeding Trinity Hospital (Fig. 4d). In this

Table 3 Slake durability index and uniaxial compressive strength of rock from different studied locations

Locations	Rock types	UCS (MPa)	Slake durability test		
			Average SDI(%)		Type
			1st cycle	2nd cycle	
Melthum Landslide	Buff Sandstone	14.8	87.55	72.02	Medium
Hlimen Landslide-1	Shale	15.7	79.82	74.27	Medium
Hlimen Landslide-2	Shale	17.9	87.82	74.22	Medium
NH-54 (a)	Shale	22.6	93.08	91.04	High
NH-54 (b)	Shale	19.4	85.39	78.37	High
NH-54 (c)	Shale	21.3	97.09	86.54	High
NH-54 (d)	Shale	17.8	93.47	83.22	High
NH-54 (e)	Shale	10.2	91.85	85.39	High
NH-54 (f)	Shale	19.5	90.4	83.52	High

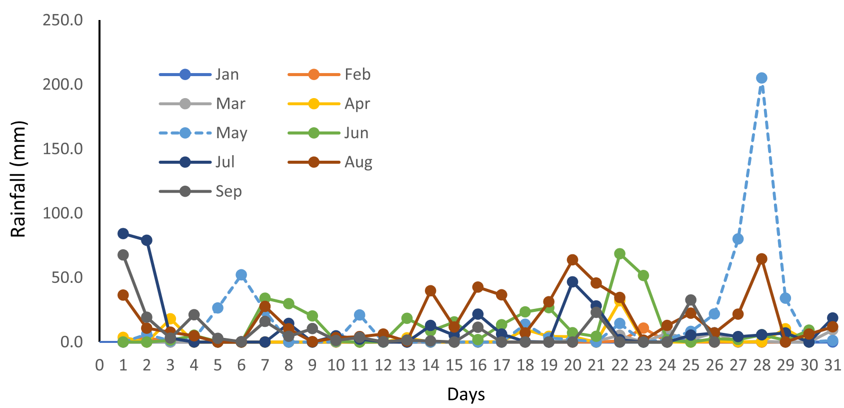


Fig. 5 The cumulative rainfall distribution of Aizawl from January–September 2024

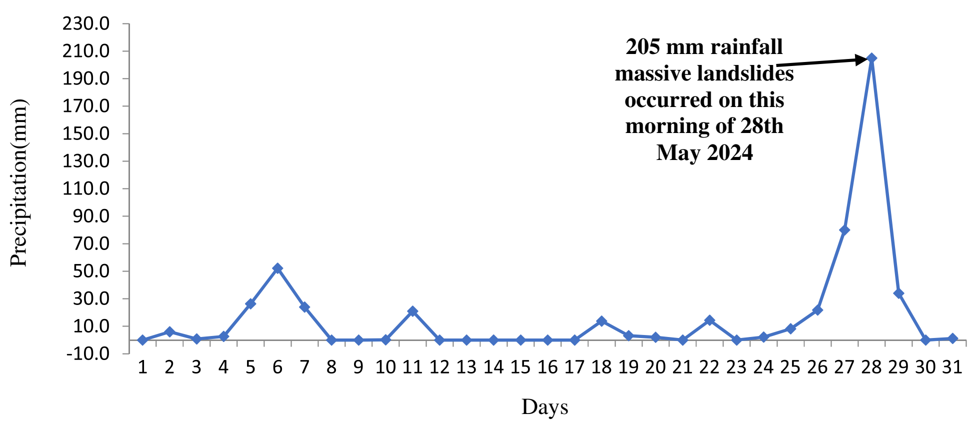


Fig. 6 The cumulative rainfall distribution for the month of May 2024

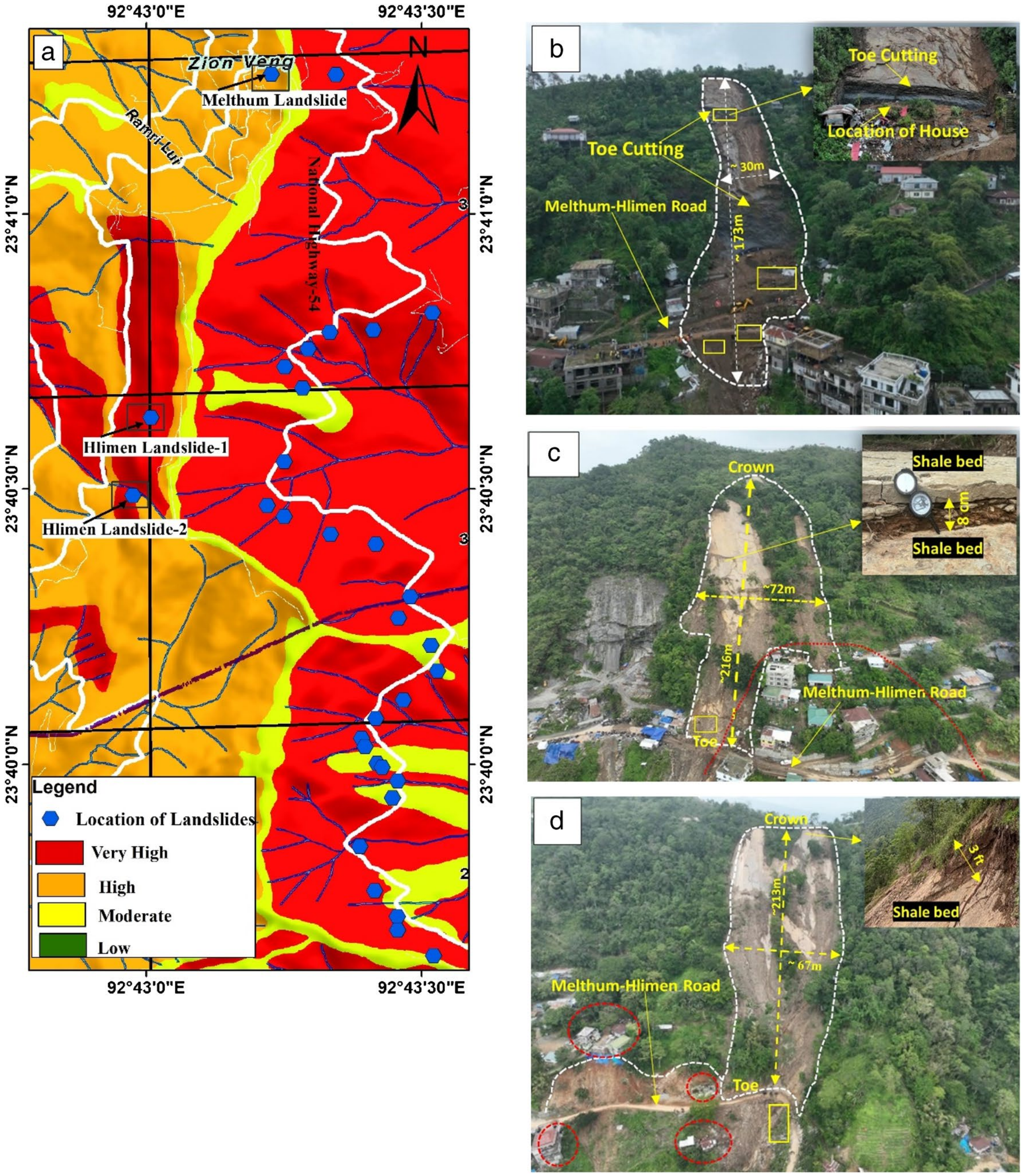


Fig. 7 Landslide location along Aizawl-Lunglei (NH-54) road and Melthum-Hlimen area. **a** Aizawl Landslide Hazard Map (data source: Aizawl Municipal Corporation, GeoHazards International. **b** Landslide at Melthum rectangle box mark the location of the building before the landslide. **c** Hlimen Landslide-1 rectangle box marks the location of the building before the landslide and red dotted lines are the affected area and 8 cm of highly fractured and weathered layer between shale bed. **d** Hlimen Landslide-2 one building collapsed marked with a rectangle box, red dotted lines were the affected buildings, and 3 ft thick intact portion at the crown

particular area, the landslide was found to be due to an unplanned, high-degree slope cutting below the hospital that was followed by the heavy rainfall of Cyclone Remal. The event invokes a threat to the patients and even to the public.

Rockfalls and debris from landslide along the road section of Aizawl-Hualngohmun (NH-54) induced blockages of the highway that disturbed transportation and rescue operations for 3 days, and hence, the victims and deceased bodies had to be carried on foot despite the high risk of the areas. Rockslides were mainly due to the high degree of joints, which caused wedge failures (Fig. 4g, h, j, and m) and planar failure (Fig. 4i and n). The landslides result in the caving of the roads, making them difficult and dangerous for movement (Fig. 4e and i).

Kinematic analysis, RMR, CoSMR, and slake durability tests were conducted in six selected locations along the Aizawl to Hualngohmun. NH-54 (sections b, c, d, and e) shows a probable

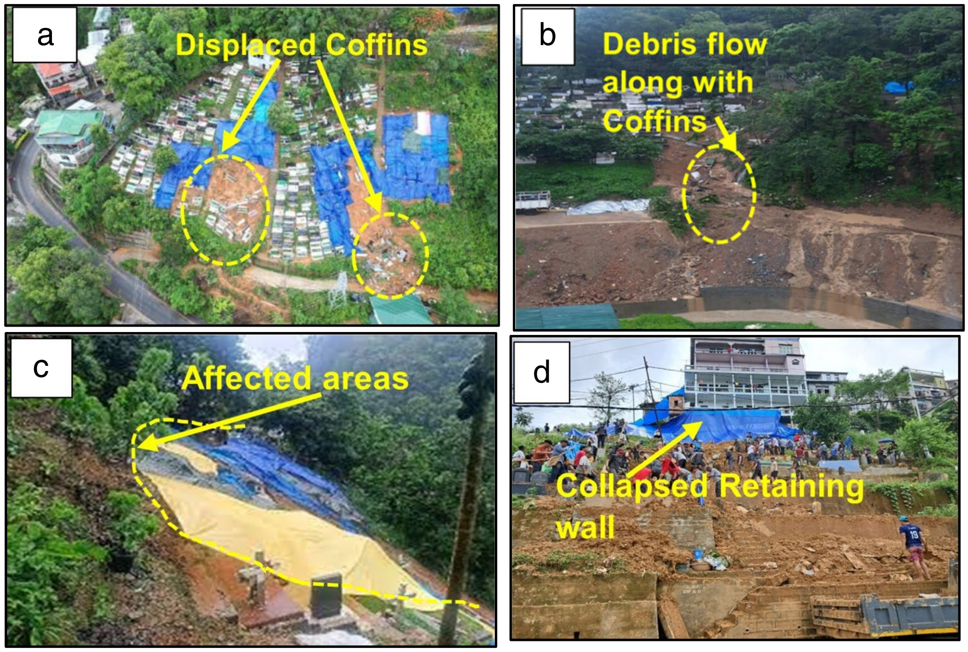


Fig. 8 **a** Landslide at ITI cemetery, displaced Coffins marked as a yellow dotted circle. **b** Landslide at Kanan cemetery, displaced Coffins marked as yellow dotted circle. **c** Landslide at Kulikawn cemetery. **d** Landslide at Republic cemetery

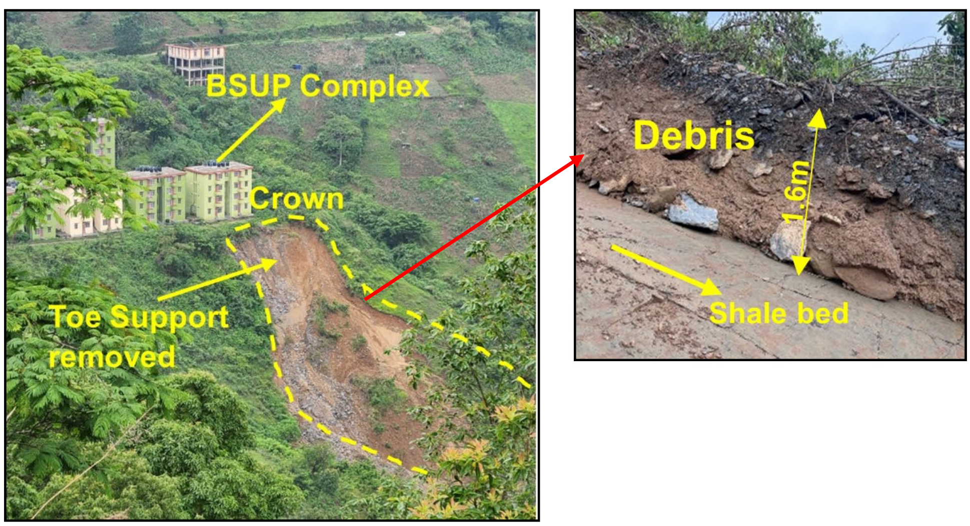


Fig. 9 Landslide in BSUP complex, Durtlang, Aizawl. The yellow line indicates the boundary of the landslide and the overburden material above the shale bed (1.6 m thick)

wedge type of failure (Table 2). The RMR value for the study area ranges between 35 to 60 (Table 1). The rock mass assessed in NH-54 (section c) falls under the "poor" rock class, having an RMR value of 35. All the other rock masses of the studied area in NH-54 (sections a, b, d, e, and f) fall under the "fair" class (Table 1). Based on CoSMR ratings, all the areas are classified as partially stable to completely unstable, with failure probabilities of 0.9 in sections c and d and between 0.4 and 0.9 in sections a, b, e, and f (Table 2). The slake durability test results show that the durability index ranges from 78.37 to 86.54%, falls under high durability (Franklin and Chandra 1972), and has a strength value ranging from 10.2 to 22.6 Mpa (Table 3). The presence of highly jointed rock mass with weak geomechanical characteristics makes the area vulnerable to rockslides, especially during intense rainfall.

Cemetery terrain failure

On 28 May 2024, four cemetery areas in Aizawl were significantly affected by landslides. More than 200 graves were displaced at the cemetery of ITI Veng (23°43′10.93″N, 92°43′59.93″E) due to the heavy rainfall of Cyclone Remal (Fig. 8a). An NGO reallocated the damaged graves and coffins. The area is covered by thick and loose soil with a high slope angle supported by only a single-laned, 4.3 m high masonry retaining wall at its toe side, which collapsed due to oversaturation of soil and improper engineering structure. Around 50 graves were displaced due to a landslide at Kanan cemetery (23°43′53.75″N, 92°42′30.43″E) (Fig. 8b). Here, the slope has an angle of 35° with a modification at the toe, featuring a 4-m-high toe cutting. It has been observed that the problem lies not with the slope cutting itself but with the poor implementation of reinforcement measures to stabilize the modified slope. Approximately 40 graves in Kulikawn cemetery (23°42′34.41″N, 92°42′58.05″E) (Fig. 8c) and 20 graves in Republic cemetery (23°43′5.76″N, 92°43′23.82″E) (Fig. 8d) were damaged due to the collapsed of retaining wall.

Heavy rainfall, improper drainage system, unplanned slope modifications, and construction of incompetent retaining walls contributed to the slope failure during heavy rainfall of Cyclone Remal. They highlighted the urgent need for comprehensive planning and mitigation measures to safeguard sacred sites and prevent further disruption.

Landslide at BSUP complex, Durtlang, Aizawl

In the complex of residential buildings constructed under the Basic Service to Urban Poor (BSUP) scheme at Durtlang (23°46′25.46″N, 92°44′38.34″E), 21 buildings were initially constructed. On the 3rd of July 2019, three buildings collapsed due to a landslide. Recently, on the 28th of May 2024, the lower portion of the complex, where the foundations of the lowermost section of the buildings were laid, slid due to heavy rainfall brought by Cyclone Remal (Fig. 9). The landslide is of debris type with a thickness of 1.6 m. The debris slide on the shale bed has a dip amount of 32°. The overburden material of soil forming the slope and the underlying shale bed have an adverse relationship facilitating shallow translational sliding.

Conclusion

The intense rainfall brought by Cyclone Remal on the 27th and 28th of May 2024 in Mizoram triggered numerous landslides and rockfalls across Aizawl at the same time at 6:30 am, leading to significant damage to property and graves, loss of lives, and destruction of residential buildings and other infrastructure. The findings indicate a societal impact, with property damage estimated at approximately Rs.3.4 crores and the tragic loss of 34 lives. Road blockages and debris with continuous rainfall in various areas hindered transportation. They had a psychological impact on both the local people and the rescue force, making it difficult and unsafe for people to carry out their daily activities and rescue operations. The landslides occurred simultaneously in different locations of Aizawl city; thus, we can infer that anomalous precipitation was the primary factor contributing to slope failures. Besides these, factors like unplanned slope modifications, poor implementation of reinforcement measures, fragile and unfavorable geological conditions of the rock mass, presence of numerous fractures, and discontinuity joint sets classify the rock mass as unstable to completely unstable under continuous slope mass rating, and poor to fair conditions under RMR make the study area highly vulnerable to slope failure during severe rainfall. Heavy rainfall, thick accumulation of loose soil, an inadequate drainage system, and toe-cutting with poor stabilization measures triggered landslides in the cemetery area. The study shows the necessity for a comprehensive understanding and detailed investigation of unplanned activities and the consequent enhancement of slope failure. The preliminary studies highlighted the critical importance of geo-engineered planning when considering geological factors. In addition, it emphasizes the need for coordinated efforts between society and government to devise hazard preparedness and emergency response strategies. Such measures are vital to minimize the impact of future events on human lives and property. To mitigate the risk of similar incidents in the future, the government needs to prioritize proper land-use planning, ensure robust infrastructure development, and identify no development zones for the vulnerable. Understanding the complex relationship between natural and anthropogenic factors will enable the development of more resilient communities. Therefore, continuous monitoring and research are essential to enhance our knowledge and preparedness for potential hazards in the region.

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Authors' contributions

All the authors participated in fieldwork and investigations across multiple sites, each bringing their expertise to the study and sharing in the manuscript design and conception. Zosangliana Ralte performed the map and photo arrangement, while Lalhmingsangi and Zosangliana Ralte wrote the manuscript.

Data availability

The data in this preliminary study is available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare no competing interests.

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