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A Preliminary Study of Rainfall-Induced Mass-Wasting Events in the Deccan Trap Terranes of Satara District, Maharashtra, India

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ABSTRACT

This paper presents a comparative geological, geomorphological, and engineering analysis of three recent rainfall-induced slope failures within the Western Ghats escarpment (Morpho-Zone Aa) of Satara District, Maharashtra, India. The studied locations include the villages of Kurulbaji (Satara Taluka), Mhate Mura (Jawali Taluka), and Sayghar (Jawali Taluka). Utilizing real-time field mapping data, structural configurations, spatial metrics, and hydro-geological observations compiled between 2025 and 2026, we characterize the failure kinematics ranging from shallow fluidic debris flows to deep-seated historical creep and anthropogenic slope instabilities. The underlying lithology across all domains consists uniform Deccan Trap basaltic lava flows capped by un-engineered, highly porous overburden of variable thickness. Our findings indicate that extreme, short-duration monsoonal precipitation acts as the primary dynamic trigger by rapidly elevating internal pore-water pressures, inducing piping action, and reducing effective shear strength along the critical soil-rock interface. The paper categorizes the vulnerabilities into structural engineering typologies, evaluates the down-gradient risk profiles to settlements, public infrastructure, and agricultural lands, and provides actionable mitigation frameworks alongside an escalation protocol for advanced geophysical modeling by the Geological Survey of India (GSI).

Keywords: GSDA, Groundwater, Landslide, western Ghat, Mhate Mura, Kurulbaji, Sayghar

1. INTRODUCTION

Rainfall-induced landslides and debris flows constitute a severe and recurring socio-economic and environmental hazard within the mountainous corridors of the Western Ghats (Sahyadri Ranges) in western India. The region's distinct geomorphology, characterized by steep stepped cliffs and deeply weathered plateau configurations derived from the Cretaceous-Paleogene Deccan Trap volcanism, renders it highly susceptible to sub-aerial mass-wasting during the Indian Summer Monsoon (ISM). Historically, these terrains have maintained a delicate balance under native forest cover; however, increasing anthropogenic slope modification via road cuts, linear infrastructure expansion, and terraced paddy farming has significantly modified natural drainage profiles and slope vectors. This paper compiles and evaluates comprehensive geological site inspection dossiers from three distinct vulnerable sites within Satara District: Kurulbaji Village (surveyed June 2025), Mhate Mura Village (surveyed July 2026), and Sayghar Village (surveyed July 2026). The primary objective is to define the boundary conditions governing slope failure, analyze the contributing hydro-geological mechanisms, and propose standardized engineering and administrative risk-mitigation blueprints.

2. Geomorphological and Administrative Framework

The three studied sites are situated within the Western Ghats escarpment zone, designated regionally as Morpho-Zone Aa. This morpho-zone is characterized by a highly undulating, rugged, and dissection-prone hilly landscape. The operational and geographic parameters established during the respective joint field investigations are synthesized in Table 1.

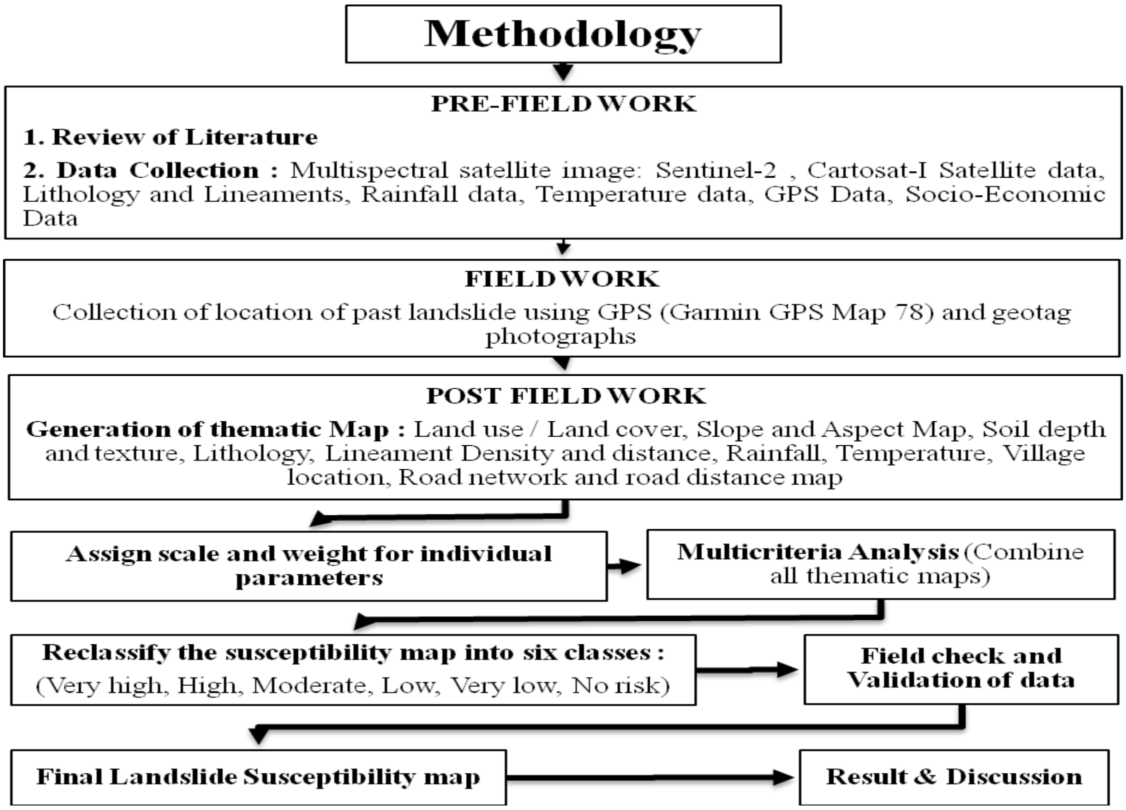
Table 1: Spatial and Technical Metrics of Surveyed Locations

Parameter	Site 1: Kurulbaji	Site 2: Mhate Mura	Site 3: Sayghar
Administrative Unit	Satara Taluka, Satara Dist.	Jawali Taluka, Satara Dist.	Jawali (Medha) Taluka, Satara Dist.
Census Code	563817	563991	564015
Survey Date	19 June 2025	10 July 2026	08 July 2026
Toposheet No.	47 G/14	47 G/13	47 G/13
Watershed / Mini Unit	KR-14 (Mini-watershed 2/18)	KR-04 (Mini-watershed 4/13)	KR-05 (Mini-watershed 3/11)
Mean Elevation (MSL)	820 metres	1060 metres	1100 metres
Geographic Coordinates	Lat: 17.704841° N Long: 73.847315° E	Lat: 17.796359° N Long: 73.785252° E	Lat: 17.850124° N Long: 73.806275° E

The spatial alignment shows a high-altitude baseline varying from 820 m to 1100 m above Mean Sea Level (MSL), positioning these communities directly beneath steep headwalls or upon thick colluvial slopes.

METHODOLOGY

Field data was gathered through rapid post-disaster mapping by joint inspection teams. Geographical coordinates, elevations, and accuracy limits were recorded at failure zones using GPS-enabled NoteCam frameworks, google earth images are also used. (Photograph No.1) Subsurface structural data was inferred from daylighting groundwater points, open tension fractures, and exposed soil-rock profiles along infrastructure cuts. All three study sites sit within Morpho-zone Aa of the Western Ghats, characterized by highly undulating, rugged basaltic hills.



3. Site-Specific Field Mapping and Spatial Observations

3.1. Kurulbaji Village (Satara Taluka)

The joint field survey executed on June 19, 2025, responded to an active slope failure tracking South of the primary residential settlement (Gaothan) at an aerial distance of approximately 500 m. The mass failure initiated on a steep hill profile trending Northeast-Southwest (NE-SW). (Photograph No.2)

Photograph No. 1- Google earth Image of Affected Study area of Kurulbaji village

West. Field tracking fixed the primary debris flow failure plane at coordinates 17°42'03.1"N, 73°50'47.2"E. Kinematic observations confirmed a distinct southward trajectory. The material involved was classified as an un-sorted, fluidic debris matrix containing coarser weathered rock fragments mixed within a highly saturated silty-clay soil profile. (Photograph No.3)

Photograph No.2 View of Landslide in Kulkajai Village

Photograph No.3 effect of Landslide in Kulkajai Village

Dynamic monitoring during the monsoonal surge revealed a slow-velocity, active debris flow. The shear force was sufficient to cause widespread root tilting and downslope tumbling of mature Eucalyptus trees embedded in the moving mass. The lateral flanks of the slide mass are bounded by first-order torrent channels (rills) that transition down-gradient into a combined second-order stream (Nala) traversing the low-lying valley basin. Notably, no immediate subsurface landmass subduction or deep-seated rotational shearing features were observed along the main scar.

Mhate Mura Village (Jawali Taluka)
The mapping operation conducted on July 10, 2026, revealed a complex, high-risk slope failure configuration distributed both upslope (South) and downslope (North) of the primary Gaothan. The village settlement is geomorphologically situated on a volatile slope transition phase, moving from upper concave accumulation profiles containing thick, cohesive colluvial soil into steep convex break-of-slopes that are highly prone to gravitational shearing seen in Google earth Image (Photograph No.4). Due to the severe structural threat, 42 resident families had been evacuated to temporary state shelters prior to the survey.

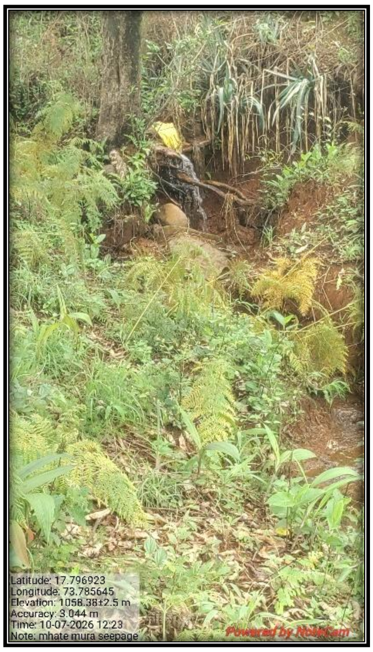
Photograph No.4 Google earth Image of Affected Study area of Mhate Kh.

Downslope Mass Creep and Tension Fracturing (North of Gaothan): An active soil avalanche zone (Photograph No.5) trending East-West propagates approximately 200 m downslope from the village edge. Prominent open tension cracks and mudcracks (Photograph No.6) were logged at coordinates 17.796629° N, 73.785876° E, indicating slow, ongoing gravitational slope creep.

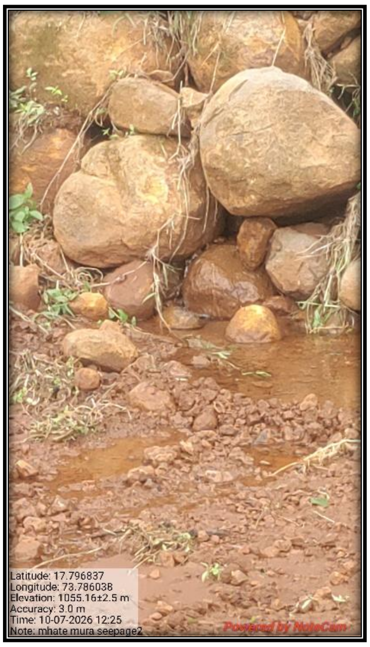
Photograph No.5 Picture showing Downslope Mass Creep

Photograph No.6 Picture showing Tension Fracturing

Subsurface Hydrogeological Daylight Points: The mid-slope zone displays extensive piping action and hyper-concentrated subsurface groundwater seepage (Photograph No.8) daylighting across multiple discharge points, which continuously feeds the destabilized matrix (Photograph No.7)



Photograph No.7 Picture showing Destabilization of matrix



Photograph No.8 Picture showing Groundwater Seepage

Upslope Structural Cut-Slope Failures (South of Gaothan): Linear Road cutting (Photograph No.10) directly south of the village has drastically modified the slope profile. Unstabilized cut-slopes have triggered active soil avalanches stretching linearly from coordinates (17.794911° N, 73.786209° E) to (17.795034° N, 73.785252° E). The failure mass consists of an unsorted weathered basaltic clay matrix (Photograph No.9) interspersed with large erratic pebbles and heavy basalt boulders (Photograph No.8).

Photograph No.9 Picture showing unsorted weathered basaltic clay

Photograph No.10 Picture showing Linear Road cutting

Historical verification confirmed a deep-seated vulnerability baseline, with significant slope subsidence events recorded locally between 1975 and 1977 directly affecting the residential structure of Kondiba Vitthal Doifode.

Sayghar Village (Jawali Taluka)

The technical investigation executed on July 8, 2026, mapped a rainfall-induced, shallow, rapid debris flow tracking approximately 95 m northeast (aerial distance) from the main village settlement (Photograph No.11). The spatial configuration of the mass movement was bounded by an Initiation Zone (Crown) at 17.850090° N, 73.805987° E and a Deposition Zone (Toe) at 17.850124° N, 73.806275° E.

The kinematics followed a strict West-to-East trajectory, terminating abruptly at the base of the hill lock. The displaced material was composed of poorly sorted, coarse angular rock fragments,

Photograph No.11 Google earth Image of Affected Study area of Mhate Kh.SayagharVillage Taluka Jaoli

basaltic saprolite, and topsoil bound together by highly saturated clay (Photograph No.11). The flow mass incorporated sheared, shallow-rooted structural vegetation, dominated by native bamboo clusters.

Photograph No.12 Picture showing Debris flow

Photograph No.13 Picture showing Soil erosion

While the primary debris lobe was temporarily static during field tracking, active rill scours and transient streamlets (<30 cm depth) were actively forming across the failure scar. In addition to the main slope failure, a secondary zone of minor surficial soil erosion ((Photograph No.13). driven by concentrated overland sheet flow was mapped 41 m east of the Gaothan. Interviews with village elders confirmed that no historical baseline of landslides or mass-wasting had ever occurred within this specific mini-watershed (KR-05) prior to this event.

Discussion on Geological Evaluation and Trigger Mechanisms

Lithology and Overburden Characteristics

The foundational geology of all three investigated sectors is defined by the thick, horizontal stack of Cretaceous-Paleogene Deccan Trap basaltic lava flows. Sub-aerial chemical weathering under humid tropical monsoonal conditions has converted the upper basaltic rinds into a highly porous, clay-rich, gravelly saprolitic soil profile.

The thickness of this un-engineered overburden layer is highly variable but represents a critical factor in slope stability. At Mhate Mura, engineering profiles indicate soil overburden depths reaching 15–20 m within the central residential Gaothan, expanding up to 30–35 m along the upper upslope infrastructure cuts. At Sayghar and Kurulbaji, the overburden represents a shallower but highly porous colluvial layer mantle resting unconformably on the dense, impermeable underlying basalt.

Anthropogenic Slope Alteration

Anthropogenic landscape modifications have severely altered the factor of safety (FS) of the native slopes. Two distinct destructive mechanisms were identified:

Paddy Terracing and Compartmentalization:
At Mhate Mura and Sayghar, hillslopes have been mechanically sculpted into flat terrace steps for agricultural cultivation. The installation of raised earthen farm bunds intentionally restricts surface runoff to facilitate prolonged water pooling. This structural arrangement forces accelerated downward hydraulic percolation, saturating the clay-rich subsoil.

Unsupported Infrastructure Cuts: Linear road excavation along steep slopes (e.g., Mhate Mura South) creates vertical, unsupported cut-faces. This layout removes lateral confining pressure from the thick soil mantle, exposing the un-sorted basaltic boulder matrix to immediate gravitational failure.

Hydro-Meteorological Mechanics

The primary dynamic trigger across all three configurations is intense, short-duration monsoonal precipitation acting upon a pre-saturated soil profile. For instance, the Sayghar debris flow occurred following intense antecedent precipitation beginning on July 5, 2026.

As heavy rainfall continues, the highly porous overburden rapidly absorbs water, increasing the total bulk weight while simultaneously elevating the internal pore-water pressure because the water cannot quickly escape through the underlying impermeable basaltic bedrock. This rapid rise in pore pressure causes a severe drop in the effective shear strength along the soil-rock boundary. The trapped groundwater acts as both a physical lubricant and a buoyant force, driving the slope past its plastic limit and triggering sudden gravity-driven debris flows or downslope mass creep.

Engineering Typology and Hazard Risk Matrix

To streamline mitigation and engineering intervention protocols, the observed failures are classified into two distinct engineering typologies (Table 2).

Table 2: Engineering Classification of Landslide Hazards

Hazard Typology	Primary Mechanism	Observed Locations	Engineering Characteristics
Type A	Agricultural soil erosion, tension cracking, and slow-moving mass creep fueled by high subsurface groundwater piping.	Mhate Mura (North Flank), Sayghar (Flank & Localized Erosion Zone).	Governed by high pore-water pressure, slow displacement, fluidic remobilization potential into mudflows.
Type B	Unsupported, over-steepened infrastructural cut-slope failures carrying heavy erratic boulders.	Mhate Mura (South Road Cutting), Kurulbaji (NE-SW steep slope face).	Sudden structural failure, high velocity, high energy impact driven by structural excavation.

A comprehensive risk receptor matrix (Table 3) outlines the predicted socio-economic and structural impacts.

Table 3: Multi-Site Hazard Risk Matrix

Location	Risk Receptor	Hazard Driver	Predicted Impact Scenario
Kurulbaji	Agricultural Lands & Secondary Valleys	Fluidic debris flow migration into the primary drainage network.	Blockage and choking of the low-lying Nala; sudden channel avulsion leading to widespread flooding of adjacent croplands.
Mhate Mura	Residential Gaothan & Linear Roads	Simultaneous upslope Type B boulder avalanches and downslope Type A creep.	Direct structural crushing of residential buildings; total closure of critical transit corridors; high mortality potential.
Sayghar	Main Settlement, ZP Water Supply, & Paddy Fields	Remobilization of upper debris lobe; high-altitude failures near infrastructure.	Structural collapse of homes; foundation undermining of the Left Elevated Storage Reservoir (ESR) & Ground Storage Reservoir (GSR).

Definitive Risk Mitigation and Actionable Recommendations

Given the steep, high-altitude positions of the primary failure zones at Kurulbaji, Mhate Mura, and Sayghar, installing direct structural retaining systems (such as extensive concrete breast walls or soil anchoring) is technically difficult and cost-prohibitive at this stage. Consequently, risk management must focus on administrative zoning, hydraulic re-engineering, and advanced inter-agency geotechnical assessment.

Immediate Public Safety and Administrative Zoning:

For communities facing immediate, high-energy threats, such as Mhate Mura and homes within the active runoff path at Sayghar, temporary relocations must be enforced throughout the monsoon season. Long-term planning must prioritize the permanent relocation of households inside the high-risk hazard zones to geologically stable areas. Strict administrative exclusion zones should be enforced along the thick soil-mantled slopes behind the settlements.

Hydraulic and Drainage Engineering: The primary downstream drainage channels (Nalas) across all sites must be immediately cleared of accumulated boulders, organic debris, and sloughed soil. Maintaining a clear, unobstructed flow path is vital to prevent channel choking, overbank flooding, and agricultural damage. Where necessary, construct engineered interceptor drains to safely route surface water away from vulnerable faces.

Inter-Agency Escalation and Advanced Geotechnical Audits: All three site files must be formally transferred to the Geological Survey of India (GSI), State Unit: Maharashtra (Pune Region), for advanced technical investigation. GSI must prioritize conducting deep core-drilling, comprehensive slope stability modeling (Factor of Safety evaluation under saturated conditions), and regional landslide susceptibility mapping. Simultaneously, the Rural Water Supply Division of the Zilla Parishad (ZP), Satara, must conduct an immediate structural safety audit at Sayghar Village to assess the foundational stability of local reservoirs.

Global and National Cross-References

Evaluating these events within a global geological context highlights clear structural differences between cratonic basalt slips and other mountain failures:

A. The Deccan Volcanic Province (Western Ghats, India)

The Deccan Volcanic Province dominated by an intense seasonal monsoon climate. Heavy, short-duration rains quickly saturate the weathered, clay-rich soil mantle (saprolite). Water moving down through vertical cooling joints pools along the flat basalt flow boundaries, causing high pore-water pressure and a loss of matrix suction. Human changes, like un-engineered cutting into steep slopes for roads and water-pooling farm bunds for paddy cultivation (as seen in Satara District), act as immediate catalysts for fast-moving translational mud-debris flows.

B. The Paraná Large Igneous Province (Serra do Mar / Serra Geral, Brazil)

The Paraná Large Igneous Province shares a close lithological equivalent with the Deccan Traps, featuring sub-horizontal flood basalts subjected to humid, tropical, high-volume rainstorms. Weathering produces exceptionally deep saprolites (often exceeding 20–30 meters in depth). High-intensity storms trigger sudden pore-pressure spikes directly along the saprolite-bedrock boundary. This triggers extremely rapid, widespread translational colluvial slips and highly fluid debris avalanches that travel down narrow valleys, causing significant structural damage to downstream infrastructure.

C. The Columbia River Basalt Group (Pacific Northwest, USA)

The Columbia River Basalt Group located in a temperate, sub-humid to semi-arid environment where failures are driven by prolonged winter rains, rapid snowmelt events, and freeze-thaw cycles. Unlike the shallow clay slips seen in tropical basalts, mass-wasting here frequently occurs as large, deep-seated slump-blocks and translational rock slides. Instability is driven by weak, water-saturated interbed sediments (such as the Ellensburg Formation) sandwiched between heavy, columnar-jointed basalt flows. River incision along corridors like the Columbia River Gorge cuts the bases of these slopes, triggering deep, rotational movements.

D. The Ethiopian Volcanic Plateau (Horn of Africa)

The Ethiopian Volcanic Plateau shows high-altitude, deeply dissected plateau characterized by extreme rugged topography and alternating wet and dry seasons. Thick sequences of Oligocene flood basalts are interbedded with weak phonolitic tuffs and ignimbrites. Weathering produces a highly unstable black cotton soil (vertisol) overburden. Heavy summer rains saturate these expandable clays, causing widespread rockfalls along steep cliffs and slow-moving, deep-seated complex earth flows that damage mountain roads and rural settlements.

The structural characteristics of these different geological regions are cross-referenced in Table 4:

Table 4: Global Comparative Matrix of Regional Landslide Dynamics

Volcanic / Structural Province	Dominant Lithological Matrix	Primary Climatic & Anthropogenic Triggers	Failure Mechanics & Typology	Kinematic / Velocity Profile
Deccan Traps *(Western Ghats, India)*	Flat-lying flood basalts; highly porous, clay-rich saprolite and red bole beds.	High-intensity seasonal monsoons; un-engineered infrastructure road cuts; terraced farm water bunds.	Pore-water pressure spikes at the soil-bedrock interface; shallow soil avalanches and translational debris flows.	Rapid to very rapid translational mud-debris flow.
Paraná Province *(Serra Geral, Brazil)*	Tholeiitic flood basalts; deep, clay-rich tropical saprolite blankets.	Torrential tropical rainstorms; heavy infrastructure cutting into mountain passes.	Structural failure along the deeply weathered saprolite-rock contact layer; extensive colluvial strip failures.	Rapid to extremely rapid debris avalanche.
Columbia River Basalt *(Pacific Northwest, USA)*	Columnar-jointed basalts interbedded with weak tuffaceous sedimentary layers.	Prolonged winter rainfall; rapid spring snowmelt; river incision at the base of slopes.	Saturated interbed failure beneath heavy basalt flows; large-scale rotational slumping and block gliding.	Slow to rapid deep-seated rotational slump / block slide.
Ethiopian Plateau *(Horn of Africa)*	Stratified flood basalts interbedded with weak tuffs, ignimbrites, and vertisols.	Intense seasonal summer rains; severe deforestation; high-gradient agricultural activities.	Cliff face undercutting via weathered tuff degradation; rockfalls, complex rotational slides, and slow creep.	Extremely rapid rockfall to slow-moving complex earth flow.

RESULT AND CONCLUSION

When evaluated within the broader context of Indian landslide geomorphology, these Western Ghats failures present sharp mechanical contrasts to the high-energy, deep-seated mountain failures seen in the Himalayan Orogenic Belt (such as the devastating Malin slide in Pune, or the major structural failures in Uttarakhand and Himachal Pradesh). Himalayan landslides are frequently driven by a combination of high-energy seismic activity, active tectonic thrusting, structural fault lines, and rapid river incision acting on weak sedimentary or metamorphic basements.

Conversely, the landslides in the Sahyadri range are classic climate-anthropogenic multi-hazard interactions targeting stable cratonic basements. The massive basalt flows themselves are structurally sound, but the surficial hazard is critically amplified by human activity. Steepening hill cuts without engineering proper retaining walls, coupled with high-percolation agricultural practices on steep slopes, creates a highly dangerous environment when subjected to climate-induced monsoonal rainfall events. The micro-regional geological investigations across Kurulbaji, Mhate Mura, and Sayghar confirm that shallow debris flows, soil avalanches, and rotational creep in District Satara are fundamentally driven by high-intensity monsoonal precipitation interacting with deep, weathered basaltic overburden. While the regional macro-topography remains basement-stable, localized engineering safety factors have been severely degraded by human activities. Un-engineered structural road cuts and water-pooling agricultural configurations serve as major catalysts that accelerate slope instability. Because structural slope stabilization is economically and logistically impractical on these high-altitude, steep terrain surfaces, civil authorities must prioritize immediate life-safety risk mitigation. To prevent catastrophic events and manage risks effectively, a multi-phased approach is recommended:

Immediate Civil Protections: Maintain seasonal and temporary evacuation protocols for high-risk residential pockets (Gaothans) during intense rainfall periods. Establish structural exclusion zones to ban human transit and livestock grazing on highly saturated slopes.

Hydraulic Engineering: Clear, de-silt, and widen downstream drainage channels (Nalas) immediately to prevent debris accumulation from choking channels, which leads to destructive avulsions and overbank flooding of adjacent agricultural lands. Implement engineered stone pitching and rip-rap reinforcements along vulnerable terraced farm boundaries.

Advanced Geotechnical Escalation: Formally transfer these dossiers to the Geological Survey of India (GSI) for definitive slope stability modeling (Factor of Safety evaluations), geophysical profiling, and deep core-drilling.

Zoning & Long-Term Relocation: Utilize GSI's comprehensive technical outputs as a blueprint to enforce regional risk mapping across Morpho-zone Aa and evaluate whether highly vulnerable villages require permanent structural relocation to geologically stable sites.

Declaration by Authors

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