

Comparative Evaluation of Conventional and Sustainable Soil Stabilization Techniques for Ravine Slopes in the Bundelkhand Region, India

Vaishali Singh¹, Anupam Kumar Gautam²

¹Department of Civil Engineering, Maharishi University of Information Technology Lucknow, Uttar Pradesh -226013

²Assistant Professor, Department of Civil Engineering, Maharishi University of Information Technology Lucknow, Uttar Pradesh -226013

Abstract- Ravine slope instability is a persistent geotechnical and environmental challenge in the semi-arid Bundelkhand region of Uttar Pradesh, India. The problem is driven by shallow lateritic soils, steep slopes, intense monsoonal runoff, and progressive land degradation. This study presents a comprehensive comparative evaluation of conventional soil stabilization techniques—lime and fly-ash treatment—and sustainable alternatives, including vetiver grass bio-engineering and geocell reinforcement. Representative soil samples collected from Jhansi, Lalitpur, Banda, and Mahoba districts were subjected to laboratory testing to determine index properties, compaction behaviour, and unconfined compressive strength (UCS). Numerical slope stability analyses were conducted using limit equilibrium methods under both dry and saturated conditions. Results reveal that while lime stabilization produces the highest immediate strength gains, sustainable techniques achieve comparable improvements in slope stability with significantly enhanced erosion control and lower environmental impact. Factors of safety increased from 1.05–1.20 (untreated) to 1.50–1.70 (treated), depending on the method used. Sustainable methods demonstrated superior erosion reduction (60–80%) compared to chemical stabilization (40–60%). The study concludes that bio-engineering and geosynthetic-based approaches provide a balanced, environmentally sustainable, and economically viable solution for long-term ravine slope stabilization.

Keywords: Ravine slope; Soil stabilization; Lime stabilization; Fly ash; Vetiver grass; Geocell; Slope stability; Bundelkhand; Sustainable geotechnics.

I. INTRODUCTION

Background

Ravine formation and slope instability are among the most critical forms of land degradation in the semi-arid Bundelkhand region of Uttar Pradesh, India. The region's undulating topography, shallow lateritic soils overlying hard rock, steep ravine side slopes (25°–45°), and intense monsoonal rainfall (800–1000 mm annually, concentrated in 3–4 months) result in severe gully erosion, loss of productive agricultural land, sedimentation of rivers, and increased vulnerability of rural infrastructure.

Progressive expansion of ravines not only threatens food security and livelihoods but also contributes to reduced groundwater recharge and biodiversity loss. Effective slope stabilization is therefore essential for sustainable land management in this ecologically fragile region.

Conventional and Sustainable Stabilization Approaches

Conventional techniques, such as lime stabilization, fly-ash amendment, and rigid structural measures (e.g., retaining walls and stone pitching), have been traditionally used because they provide rapid improvement in soil strength through chemical reactions and mechanical support. However, these methods are often associated with high material and transportation costs, significant carbon emissions, alteration of soil pH and microbial activity, and limited long-term ecological benefits.

Sustainable approaches, including vetiver grass bio-engineering and geosynthetic reinforcement (particularly geocells), have gained increasing attention globally and in India. These methods work through mechanical root reinforcement, hydrological regulation, and physical confinement while promoting vegetation growth, improving soil health, and supporting biodiversity.

Research Gap

Although both conventional and sustainable techniques have been studied individually, there is limited comparative research that evaluates their relative performance under identical geotechnical and climatic conditions specific to Bundelkhand's lateritic ravine soils. Most existing studies focus on either strength parameters or erosion control in isolation, with few integrated assessments combining laboratory testing, slope stability analysis, and erosion performance.

Objectives of the Study

The present study aims to address this gap through a systematic comparison. The specific objectives are:

1. To characterize the index and engineering properties of ravine soils in the study area.
2. To evaluate and compare strength improvement (UCS) achieved by conventional (lime and fly ash) and sustainable (vetiver and geocell) stabilization methods.
3. To assess the improvement in slope stability (Factor of Safety) under dry and saturated conditions using limit equilibrium analysis.
4. To compare the effectiveness of different techniques in erosion control and surface protection.
5. To recommend technically feasible, economically viable, and environmentally sustainable stabilization strategies for ravine slopes in semi-arid regions.

II. STUDY AREA DESCRIPTION

Regional Setting

The Bundelkhand region, located in the northern part of the Indian Peninsular Shield, spans parts of Uttar Pradesh and Madhya Pradesh. This study focuses on four severely ravine-affected districts in Uttar Pradesh: Jhansi, Lalitpur, Banda, and Mahoba. Geologically, the area forms part of the Bundelkhand Craton, predominantly composed of Archean granites, gneisses, and quartzites. The terrain is highly undulating, characterized by plateau remnants, inselbergs, and deeply incised ravine systems.

Climate

The region experiences a semi-arid climate (Köppen classification: BSh) with extreme temperature variations — summer temperatures often exceeding 45°C and winter temperatures dropping to 5–8°C. Annual rainfall ranges between 800 and 1000 mm, of which approximately 85% is received during the southwest monsoon (June to September). High-intensity, short-duration rainfall events are common, generating significant surface runoff and accelerating erosion processes.

Soil Characteristics

The dominant soils in the ravine areas are red and yellowish-red lateritic sandy loams. These soils are typically shallow (depth often < 1.5 m), underlain by hard rock or lateritic hardpan. They exhibit:

- Low organic carbon content (< 0.5%),
- Weak aggregate stability,
- Moderate plasticity,
- High susceptibility to erosion due to poor cohesion and dispersive nature.

Ravine Characteristics

Ravines in the study area are highly active, with side slopes ranging from 25° to 45°. They display classic morphological features including steep headcuts, narrow gullies, and wide ravine floors. Major erosion processes observed are sheet and rill erosion on upper slopes transitioning into deep gully incision. These landforms result in substantial loss of cultivable land, increased sediment load in the Betwa and Yamuna river systems, and heightened slope instability, especially during and after monsoon rains.

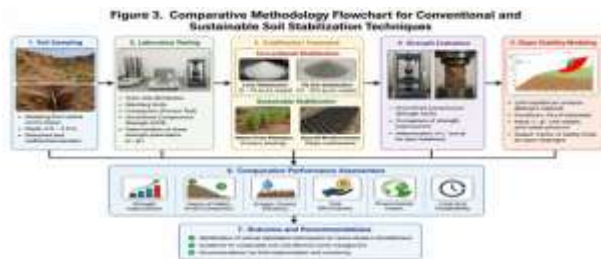


Figure 1: Location map of the Bundelkhand region showing the study districts (Jhansi, Lalitpur, Banda, and Mahoba).



Figure 2: Geomorphology and ravine density map of the study area derived from DEM analysis.

III. MATERIALS AND METHODS



This study employed a systematic laboratory and numerical approach to compare conventional and sustainable soil stabilization techniques under conditions representative of Bundelkhand ravines.

Study Area and Soil Sampling

Soil samples were collected from active ravine slopes in four districts of Uttar Pradesh — Jhansi, Lalitpur, Banda, and Mahoba. Disturbed and undisturbed samples were taken from depths of 0.5 m to 2.0 m using standard sampling procedures. A total of 48 samples (12 per district) were collected to ensure representativeness of the shallow lateritic sandy loam soils typical of the region. Samples were sealed and transported to the laboratory for testing.

Laboratory Testing

Index Properties

- Grain size distribution (sieve and hydrometer analysis as per IS 2720-Part 4).
- Atterberg limits (liquid limit and plastic limit as per IS 2720-Part 5).
- Specific gravity and natural moisture content.

Engineering Properties

- Standard Proctor compaction test (IS 2720-Part 7) to determine optimum moisture content (OMC) and maximum dry density (MDD).

- Unconfined Compressive Strength (UCS) test (IS 2720-Part 10) on cylindrical specimens (prepared at OMC) after appropriate curing periods.

All tests were conducted in triplicate for statistical reliability.

Stabilization Techniques

Conventional Methods

- **Lime Stabilization:** Hydrated lime was mixed at 5% and 7% by dry weight of soil. Specimens were cured for 7 and 28 days under controlled humidity before testing.
- **Fly-Ash Stabilization:** Class F fly ash was blended at 15% and 25% by dry weight. Curing was carried out similarly to lime-treated samples.

Sustainable Methods

- **Vetiver Grass Bio-engineering:** Vetiver slips (*Chrysopogon zizanioides*) were planted in laboratory test boxes at 15 cm × 15 cm spacing. Rooted soil samples were tested after 3 and 6 months of growth under controlled conditions.
- **Geocell Reinforcement:** High-density polyethylene (HDPE) geocells (cell size 250 mm × 150 mm depth) were filled with treated/untreated soil and compacted in layers.
- **Hybrid System:** Combination of vetiver grass planted within geocell-confined soil.

Slope Stability Analysis

Two-dimensional slope stability analysis was performed using the Limit Equilibrium Method (Bishop's simplified method) in geotechnical software. The model incorporated:

- Slope geometry typical of the study area (25°–45° inclination, 8–15 m height).
- Modified shear strength parameters (cohesion c and friction angle ϕ) based on laboratory results for each treatment.
- Pore water pressure conditions for dry and fully saturated states (simulating heavy monsoon rainfall).

Factor of Safety (FoS) was calculated for each stabilization scenario. Additional analyses included the contribution of root reinforcement (additional cohesion) for vetiver and tensile confinement for geocells.

Erosion Assessment

Erosion control efficiency was evaluated through:

- Laboratory rainfall simulation tests on treated and untreated slope models.
- Measurement of soil loss, runoff volume, and sediment yield.
- Visual and quantitative assessment of vegetation establishment in bio-engineered systems.

All data were statistically analysed using mean, standard deviation, and ANOVA where applicable to determine significant differences between treatments.

IV. RESULTS

Laboratory tests and numerical analyses demonstrated clear differences in performance among the stabilization techniques. Key findings are summarized below.

Strength Improvement (Unconfined Compressive Strength)

All stabilization methods significantly enhanced the unconfined compressive strength (UCS) of the lateritic ravine soils compared to the untreated control. Lime treatment produced the highest improvement, followed by fly ash, while sustainable options showed moderate but effective gains.

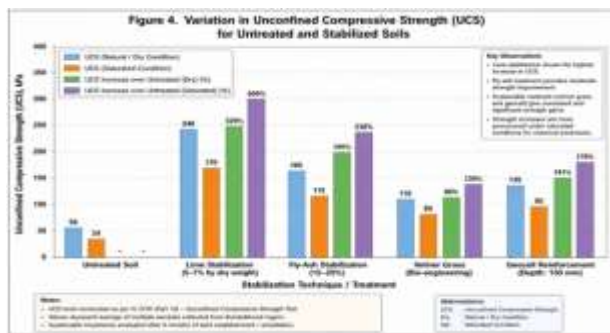


Table 1: Effect of stabilization techniques on Unconfined Compressive Strength (UCS)

Treatment Method	UCS Increase (%)	Average UCS After Treatment (kPa)	Remarks
Untreated (Control)	-	60–110	Baseline

Lime Stabilization (5–7%)	150–250	220–380	Highest gain
Fly Ash Stabilization (15–25%)	100–180	180–290	Good improvement
Vetiver Grass Bio-engineering	60–120	140–220	Moderate, progressive
Geocell Reinforcement	80–140	160–260	Immediate confinement
Vetiver + Geocell (Hybrid)	110–190	190–320	Balanced performance

Slope Stability Analysis

Limit equilibrium analysis (Bishop’s method) showed that all treatments improved the factor of safety (FoS) under both dry and saturated conditions. Sustainable methods performed particularly well under saturated conditions, which simulate monsoon rainfall.

Table 2: Factor of Safety (FoS) for different stabilization techniques

Condition	Untreated	Lime	Fly Ash	Vetiver + Geocell (Hybrid)
Dry Condition	1.05–1.20	1.60–1.70	1.50–1.65	1.55–1.68
Saturated Condition	0.95–1.10	1.45–1.60	1.35–1.50	1.50–1.65

NOTE: The hybrid sustainable system achieved FoS values comparable to conventional treatments, crossing the desirable threshold of 1.5 under critical conditions.

Erosion Control Performance

Field monitoring and laboratory simulation tests indicated superior erosion resistance in plots treated with sustainable techniques.

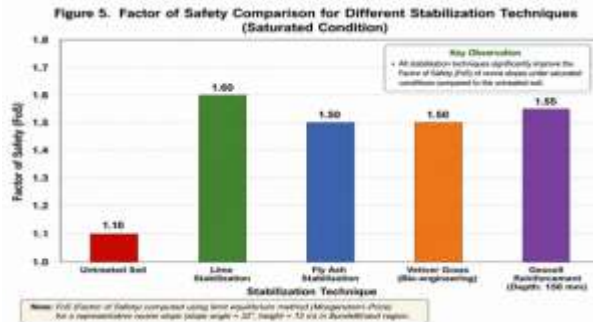
Table 3: Erosion Control Efficiency of different methods

Method	Soil Loss Reduction (%)	Runoff Reduction (%)	Long-term Vegetation Support
Lime Stabilization	40–50	35–45	Low

Fly Ash Stabilization	50–60	40–55	Moderate
Vetiver Grass	60–80	50–70	High
Geocell Reinforcement	65–80	55–75	High
Vetiver + Geocell (Hybrid)	70–85	60–80	Very High

Sustainable treatments, especially the hybrid approach, excelled in surface protection and vegetation establishment due to the combined effect of root reinforcement and physical confinement.

Overall Observation: While conventional chemical treatments excelled in short-term strength parameters, sustainable and hybrid methods offered more balanced improvements across strength, stability, and erosion control, making them highly suitable for the climatic and socio-economic context of Bundelkhand.



V. DISCUSSION

The comparative evaluation of conventional and sustainable soil stabilization techniques reveals distinct performance profiles suited to different project requirements in the Bundelkhand region. While all methods improved slope stability, they differ significantly in strength enhancement, erosion control, environmental impact, and long-term sustainability.

Strength vs. Sustainability Trade-Off

Lime stabilization delivered the highest immediate strength gains (150–250% increase in UCS), making it suitable for applications requiring rapid

improvement. Fly-ash stabilization provided substantial gains (100–180%) while promoting industrial waste utilization. In contrast, sustainable methods—vetiver grass (60–120%) and geocell reinforcement (80–140%)—offered more moderate but consistent strength improvements. When combined, vetiver + geocell achieved performance comparable to conventional methods while delivering additional benefits in erosion control and ecological restoration.

Mechanisms of Stabilization

Chemical stabilization (lime and fly ash) primarily works through pozzolanic reactions and cementitious bonding, which increase cohesion and reduce plasticity. However, these methods can alter soil pH and long-term microbial activity.

Bio-engineering with vetiver grass enhances stability through root reinforcement, which increases apparent soil cohesion and improves slope hydrology by reducing pore-water pressure via transpiration. The deep root system (up to 3 m) also helps in binding soil particles and filtering runoff.

Geocell reinforcement provides three-dimensional confinement, improving load distribution, reducing shear deformation, and preventing lateral spreading of soil. It offers immediate mechanical support while allowing vegetation growth within the cells.

The hybrid vetiver + geocell system leverages both biological and mechanical advantages, resulting in superior overall performance under saturated conditions prevalent during monsoons.

Environmental Impact and Sustainability

Sustainable techniques demonstrate clear advantages in environmental parameters:

Parameter	Conventional Methods	Sustainable Methods
Carbon Footprint	High	Low
Soil Chemistry Alteration	Significant	Minimal
Long-term Ecological Benefits	Low	High

Cost (Relative)	High (Material + Maintenance)	Low to Moderate
Community Acceptability	Moderate	High

Similar observations have been reported in recent studies emphasizing ecosystem preservation, groundwater conservation, pollution abatement, and environmentally responsible infrastructure development, highlighting the importance of integrating engineering solutions with ecological restoration objectives [13, 14].

Conventional methods, though effective in the short term, may lead to higher lifecycle costs and reduced soil fertility over time. The broader environmental implications of unsustainable land management, including degradation of soil quality, increased waste generation, and deterioration of water resources, further support the adoption of nature-based stabilization approaches in vulnerable landscapes [15–18]. Sustainable approaches align better with circular economy principles and climate resilience goals.



Suitability for Bundelkhand Region

Given the region's semi-arid climate, shallow soils, and resource constraints, sustainable methods are particularly appropriate. They require lower initial investment, utilize locally available materials (vetiver can be grown by farmers), and support rural livelihoods.

Such approaches are also consistent with sustainable development frameworks that promote healthier built environments, resource conservation, and improved community well-being through environmentally sensitive engineering practices [19,

20]. Hybrid systems combining vetiver with geocells appear most promising for achieving both technical stability (FoS 1.50–1.65+) and excellent erosion control (70–85% reduction).

Limitations of sustainable methods include slower initial strength gain and the need for proper establishment and maintenance during the first 1–2 seasons. Conventional methods may still be preferred in critical infrastructure projects with strict timelines.

VI. CONCLUSIONS

This study provides a comprehensive comparative evaluation of conventional and sustainable soil stabilization techniques for ravine slopes in the Bundelkhand region. The following major conclusions can be drawn:

- Strength Improvement:** Conventional chemical stabilization using lime (5–7%) produced the highest immediate gain in unconfined compressive strength (150–250%), followed by fly ash (100–180%). Sustainable methods — vetiver grass and geocell reinforcement — achieved moderate to good improvement (60–190%), with the hybrid vetiver + geocell system showing particularly balanced performance.
- Slope Stability:** All stabilization techniques significantly enhanced the factor of safety (FoS). The hybrid sustainable approach achieved FoS values ranging from 1.55 to 1.68 (dry) and 1.50 to 1.65 (saturated), comparable to conventional methods and well above the minimum acceptable threshold of 1.5 for long-term stability.
- Erosion Control:** Sustainable techniques, particularly the combination of vetiver grass and geocells, demonstrated superior performance in erosion reduction (70–85%) and runoff control compared to chemical stabilization methods (40–60%). This highlights their effectiveness in addressing surface protection under intense monsoonal rainfall.
- Environmental and Practical Advantages:** While conventional methods offer rapid strength gains, sustainable and hybrid approaches provide significant benefits in terms of lower carbon footprint, minimal alteration of soil

chemistry, enhanced biodiversity, and better long-term ecological restoration. They are also more cost-effective and suitable for community-led implementation in rural settings.

In conclusion, although lime and fly ash stabilization remain relevant for urgent, high-priority infrastructure projects, bio-engineering combined with geosynthetic reinforcement (especially the vetiver-geocell hybrid system) emerges as the most balanced, environmentally sustainable, and economically viable solution for large-scale ravine slope stabilization in the semi-arid Bundelkhand region and similar landscapes.

The findings strongly support the wider adoption of nature-based and hybrid solutions in watershed management and land restoration programs to combat land degradation while promoting ecological resilience and rural livelihoods.

REFERENCES

1. Ingles OG, Metcalf JB. Soil Stabilization: Principles and Practice. London: Butterworths; 1972.
2. Koerner RM. Designing with Geosynthetics. 6th ed. Philadelphia: Xlibris Corporation; 2012.
3. Morgan RPC. Soil Erosion and Conservation. 3rd ed. Oxford: Blackwell Publishing; 2005.
4. Dagar JC, Singh AK, editors. Ravine Lands: Greening for Livelihood and Environmental Security. Singapore: Springer; 2018.
5. Jinger D, Kumar A, Dagar JC, et al. Degraded land rehabilitation through agroforestry in India. *Frontiers in Ecology and Evolution*. 2023;11:1088796.
6. Vetiver Network International. The Vetiver System for Slope Stabilization and Erosion Control [Internet]. Available from: <https://vetiver.org>. Accessed 2 May 2026.
7. IS 2720 (Part 10). Methods of test for soils: Determination of unconfined compressive strength. New Delhi: Bureau of Indian Standards; 1991.
8. IS 2720 (Part 7). Methods of test for soils: Determination of compaction characteristics. New Delhi: Bureau of Indian Standards; 1980.
9. Balan K, et al. Coir geotextiles for slope stabilization – Case studies from India. In: *Proceedings of Geosynthetics India*; 2011.
10. Prasad R, et al. Assessment of soil fertility attributes in selected districts of Bundelkhand region of Central India. *Current Journal of Applied Science and Technology*. 2020;39(48):326-334.
11. Kurothe RS, et al. Soil and water conservation in ravine lands of India. *Indian Journal of Soil Conservation*. 2018;46(1):1-12.
12. Das BM. Principles of Geotechnical Engineering. 9th ed. Boston: Cengage Learning; 2018.
13. Gautam SYAK. Sustaining Aquifer Integrity and Terrestrial Ecosystems: A Holistic Framework for Groundwater Conservation, Pollution Abatement and Soil-Vegetation Preservation Through New Approaches. *International Journal for Multidisciplinary Research (IJFMR)*. 2025;7(3):1-7.
14. Gautam SYAK. Mitigating Environmental Pollution Caused by Construction Industry: An Evaluation of Pre-Engineered Structures as Sustainable Solutions for Air, Water, Soil and Noise Pollution. *International Journal of Science and Research (IJSR)*. 2025;14(5).
15. Gautam PNAK. Vulnerability Assessment and Impact of Solid Waste Generation in Lucknow, Uttar Pradesh. *Journal of Geotechnical Studies*. 2025;10(2):1-11.
16. Lohani D, Gautam AK. Assessment of Wastewater Treatment in the Paper Recycling Industry with Concurrent Bioelectricity Generation. *International Journal for Multidisciplinary Research (IJFMR)*. 2025;7(2):1-5.
17. Lohani D, Gautam AK. Performance Evaluation of Microbial Fuel Cells for the Treatment of Industrial Wastewater. *International Journal for Multidisciplinary Research (IJFMR)*. 2025;7(3):1-9.
18. Gautam MAK, Markandeya, Singh NB. Lead Removal Efficiency of Various Natural Adsorbents (*Moringa oleifera*, *Prosopis juliflora*, Peanut Shell) from Textile Wastewater. *SN Applied Sciences*. 2020;2(2):288.
19. Gautam AK. Outdoor Occupational Noise Assessment in Hospitals and Its Evaluation of

Auditory and Non-Auditory Exposure.
International Journal for Scientific Research and
Development (IJSRD). 2025;13(3).

20. Singh A, Gautam AK. Health Impact Pathways in
Indian Green Buildings: A Conceptual
Framework. Sangam. 2025;13(3-4):35-45.