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Sustainable landslide mitigation strategies: A review of Nature-based solutions

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Abstract**—**Landslides are among the most devastating natural hazards, exacerbated by climate change, deforestation, and rapid urbanization. Conventional engineering measures such as retaining walls, drainage systems, and slope reinforcement can be effective but are often costly, environmentally disruptive, and not always sustainable in the long term. Nature-based solutions (NBS) have recently gained recognition as an alternative approach that leverages ecological processes to stabilize slopes while providing co-benefits for biodiversity, water management, and local communities. This review focuses on various NBS methods for landslide mitigation, including afforestation, bioengineering, slope vegetation cover, and watershed management practices. Case studies demonstrate how vegetation root reinforcement, agroforestry, and ecological buffers contribute to reducing slope instability and sediment displacement. The review findings suggest that NBS are environmentally friendly, economically viable, socially acceptable, and adaptable to local conditions. However, challenges remain due to time-intensive establishment, site-specific performance variability, and the absence of standardized evaluation systems, which hinder large-scale implementation. Future directions emphasize the integration of NBS with geotechnical monitoring and engineering solutions, the use of remote sensing and artificial intelligence for performance assessment, and active community involvement to enhance long-term sustainability.

Keywords— Landslide mitigation, nature-based solutions, slope stabilization, bioengineering, sustainable disaster management, climate adaptation.

I. INTRODUCTION

Landslides are among the most destructive natural hazards, causing extensive socio-economic losses, fatalities, and long-term environmental degradation worldwide. They occur across diverse landscapes, particularly in mountainous regions and urban fringes, where deforestation, infrastructure expansion, and unplanned land use significantly increase vulnerability. Global disaster risk reports indicate that thousands of people die annually from landslides, which also damage critical infrastructure such as roads, bridges, and agricultural land. The growing frequency and intensity of extreme rainfall events linked to climate change have further intensified slope failures, making landslides a major concern within disaster risk management and sustainable development frameworks [20].

Conventional engineering measures—such as retaining walls, slope excavation, gabion structures, rock bolts, and drainage systems—have long been employed to mitigate landslides. Although technically effective, these measures are often costly, resource-intensive, and environmentally intrusive [16]. For instance, massive retaining walls and concrete structures can disrupt natural drainage patterns, degrade ecosystems, and inhibit vegetation growth, thereby conflicting with modern sustainability goals emphasizing ecosystem preservation, carbon neutrality, and long-term resilience. These limitations underscore the need for more sustainable, adaptive, and ecologically compatible alternatives.

In recent years, **Nature-based Solutions (NbS)** have emerged as promising complements to traditional engineering approaches. NbS involve the conservation, sustainable management, and restoration of natural or modified ecosystems to address societal challenges, including disaster risk reduction. In the context of landslide mitigation, NbS harness ecological functions such as root reinforcement, hydrological regulation, and soil cohesion to enhance slope stability. Vegetation cover—comprising forests, shrubs, and grasses—binds soil particles, improves infiltration, and reduces surface runoff. Techniques such as bioengineering, afforestation, agroforestry, and watershed management not only decrease landslide susceptibility but also enhance biodiversity, carbon sequestration, and community resilience [6].

Considering the limitations of conventional engineering practices and the resource constraints faced by many developing regions, NbS offer cost-effective, sustainable alternatives that strengthen natural buffers and promote climate resilience. Accordingly, this review aims to (i) summarize current NbS practices for landslide mitigation worldwide; (ii) compare their effectiveness with traditional engineering measures; and (iii) identify research gaps, implementation challenges, and future directions related to climate adaptation, policy integration, and community participation [18].

Nature-based landslide mitigation methods utilize ecological and ecosystem-based approaches—such as vegetation, soil bioengineering, reforestation, and hydrological management—to enhance the natural stability of slopes. Unlike hard engineering structures, these methods are sustainable, cost-effective, and provide multiple co-benefits, including biodiversity conservation, improved soil fertility, water quality, and carbon sequestration. Vegetative stabilization using deep-rooted grasses, shrubs, and trees strengthens slopes by binding soil particles and reducing erosion; commonly used species include vetiver, bamboo, willow, and native trees. Agroforestry and land management practices—such as contour farming, terracing, and cover cropping—integrate vegetation into agriculture to reduce runoff and soil loss while maintaining productivity. Bioengineering combines vegetation with simple structures, including live check dams, brush layering, fascines, and vegetated geogrids, to stabilize gullies and reinforce slopes. Reforestation and afforestation restore forest cover, improving hydrological balance and anchoring soil through dense root networks. Eco-drainage systems like vegetated swales, buffer strips, and wetlands further regulate runoff and pore pressure. Soil bioengineering and vegetated terracing also enhance slope strength, reduce erosion, and support sustainable cultivation in hilly terrain.

Community-based ecosystem management is crucial for the long-term effectiveness of nature-based landslide mitigation, as local communities often revive traditional practices such as stone bunding, vegetated terraces, and bamboo check dams that integrate indigenous knowledge with modern ecological principles. This participatory approach not only enhances slope stability but also strengthens resilience among vulnerable populations. Overall, nature-based methods are adaptive, environmentally sustainable, and offer multiple ecosystem services; however, they typically require longer periods to achieve effectiveness and are most suitable when combined with structural measures for managing large or deep-seated landslides.

Novelty and Contribution

Although extensive research has been conducted on landslide mitigation, most studies either emphasize engineering-based methods or assess Nature-based Solutions (NbS) in isolation without broad comparative analysis. This review stands out by integrating sustainable landslide reduction approaches within the NbS framework, linking ecological, engineering, and disaster risk management perspectives [8]. The novelty lies in its multiperspective approach that combines ecological, hydrological, geotechnical, and socio-economic dimensions, highlighting complementarities between NbS and conventional engineering rather than competition. It also addresses practical limitations of NbS, including long establishment periods, spatial variability, and monitoring challenges, while identifying future research needs related to hybrid NbS–engineering systems, advanced geotechnical monitoring, and global policy integration. The paper contributes through a comprehensive analysis of international studies evaluating NbS effectiveness under varying climatic and ecological settings, a comparative assessment of NbS and traditional methods to achieve cost-effective and biodiversity-supportive solutions, and an identification of policy, financial, and technical barriers hindering large-scale adoption. Moreover, it proposes a predictive framework for integrating NbS into disaster risk reduction strategies that emphasize hybrid approaches, community participation, and climate resilience. Overall, the study unites diverse disciplinary insights to influence both research and policy, positioning NbS as integral components of sustainable landslide management that balance hazard reduction with broader environmental and societal goals [9].

II. RELATED WORKS

Landslide mitigation research has progressively shifted from conventional engineering-based approaches to more ecological and sustainable practices. Earlier methods such as retaining walls, terracing, and slope reinforcement offered short-term stability but were expensive and environmentally intrusive. Subsequent studies highlighted the importance of vegetation in enhancing slope stability by increasing soil cohesion, shear strength, and infiltration while reducing surface runoff. Forests, grasslands, and mixed vegetation covers have proven effective in erosion control, encouraging afforestation, reforestation, and agroforestry as natural preventive measures [17]. Bioengineering techniques—such as brush layering, live staking, and vegetated geogrids—combine vegetation with structural materials for stabilizing shallow slopes and supporting post-disaster restoration. Integrated watershed management, involving vegetation recovery, drainage control, and soil conservation, further reduces slope instability. Comparative analyses indicate that although Nature-based Solutions (NbS) require more time to reach full functionality, they are more sustainable, cost-effective, and beneficial for biodiversity, carbon sequestration, and community livelihoods [7]. Global case studies confirm that reforestation, grass and shrub planting, and integrated forest–water management reduce landslide frequency and improve ecosystem resilience [19]. However, NbS effectiveness varies with soil, climate, vegetation type, and management practices, while the absence of standardized monitoring methods and long-term data limits cross-site comparison. Hybrid NbS–engineering systems have been recommended, particularly in high-risk areas, to combine ecological and structural stability. The success of NbS also depends on governance, community involvement, and financial support for mainstream adoption. Overall, studies affirm that NbS are technically viable and align with global sustainability, climate adaptation, and ecosystem restoration goals, serving as integral rather than supplementary components of modern landslide mitigation [10].

III. PROPOSED METHODOLOGY

The proposed methodology adopts an integrated modeling and evaluation framework that combines slope stability analysis, vegetation reinforcement modeling, hydrological balance assessment, and hybrid NbS engineering approaches. The methodology is structured in four phases: data acquisition, mathematical modeling, simulation of vegetation and hydrological effects, and performance evaluation [15].

Slope Stability Modeling

The stability of slopes is evaluated using the Factor of Safety (FoS) approach. FoS represents the ratio of resisting forces to driving forces acting on a potential sliding mass.

$$FoS = \frac{R}{D} \qquad (1)$$

where R is the total resisting force and D is the driving force due to gravity and external loads. A slope is stable when FoS > 1.0.

The driving force for a soil mass on a slope is expressed as:

$$D = W \cdot \sin(\theta) \qquad (2)$$

where W is the soil weight and θ is the slope angle.

The resisting force is primarily contributed by soil shear strength, given by the Mohr-Coulomb criterion:

$$R = c \cdot L + N \cdot \tan(\phi) \tag{3}$$

where c is soil cohesion, L is the length of the slip surface, N is the normal force, and ϕ is the internal friction angle [13].

Vegetation Reinforcement

Vegetation roots add an additional component of apparent cohesion to soil strength. This can be expressed as:

$$c_{eff} = c + c_{\text{root}} \tag{4}$$

where c_{eff} is effective cohesion and c_{root} is cohesion contributed by roots.

The reinforcement provided by roots is quantified as:

$$c_{\text{root}} = \frac{T_r \cdot A_r}{A_s} \tag{5}$$

where T_r is root tensile strength, A_r is total root area crossing the slip plane, and A_s is soil area along the slip surface.

Hydrological Influence

Water pressure is a major destabilizing factor in landslides. The pore water pressure, u, is computed as:

$$u = \gamma_w \cdot h \tag{6}$$

where γ_w is the unit weight of water and h is the height of the water table above the slip surface. Effective stress, which governs soil shear strength, is given as:

$$\sigma' = \sigma - u \tag{7}$$

where σ is total stress and σ' is effective stress.

The infiltration of rainfall is modeled by the Green-Ampt approximation:

$$f(t) = K_s \left(1 + \frac{\Psi \cdot \Delta\theta}{F(t)}\right) \tag{8}$$

where K_s is saturated hydraulic conductivity, Ψ is soil suction head, $\Delta\theta$ is change in water content, and $F(t)$ is cumulative infiltration.

Factor of Safety with Vegetation and Hydrology

The integrated FoS including vegetation and hydrological effects is written as:

$$FoS = \frac{c_{eff} + (\sigma - u) \cdot \tan(\phi)}{\tau} \tag{9}$$

where τ is the shear stress mobilized along the slip plane [12].

This formulation explicitly includes vegetation reinforcement and pore water pressure reduction, allowing comparison between engineered and NbS-based slopes.

Hybrid NbS-Engineering Model

In high-risk slopes, hybrid solutions combine vegetation cover with engineering reinforcements. The performance index is computed as:

$$PI = \alpha \cdot FoS_{NbS} + \beta \cdot FoS_{Eng} \tag{10}$$

where α and β are weighting factors depending on vegetation maturity and structural reinforcement. The cost-effectiveness ratio is then assessed as:

$$CER = \frac{C_{\text{total}}}{FoS_{\text{final}}} \tag{11}$$

where C_{total} is the combined implementation cost and FOS_{final} is the achieved factor of safety [14].

The figure 1 demonstrates the iterative process of incorporating the hazard assessment process, NbS design process, implementation process, monitoring process and adaptive management process in order to gain long-term sustainable landslide mitigation.

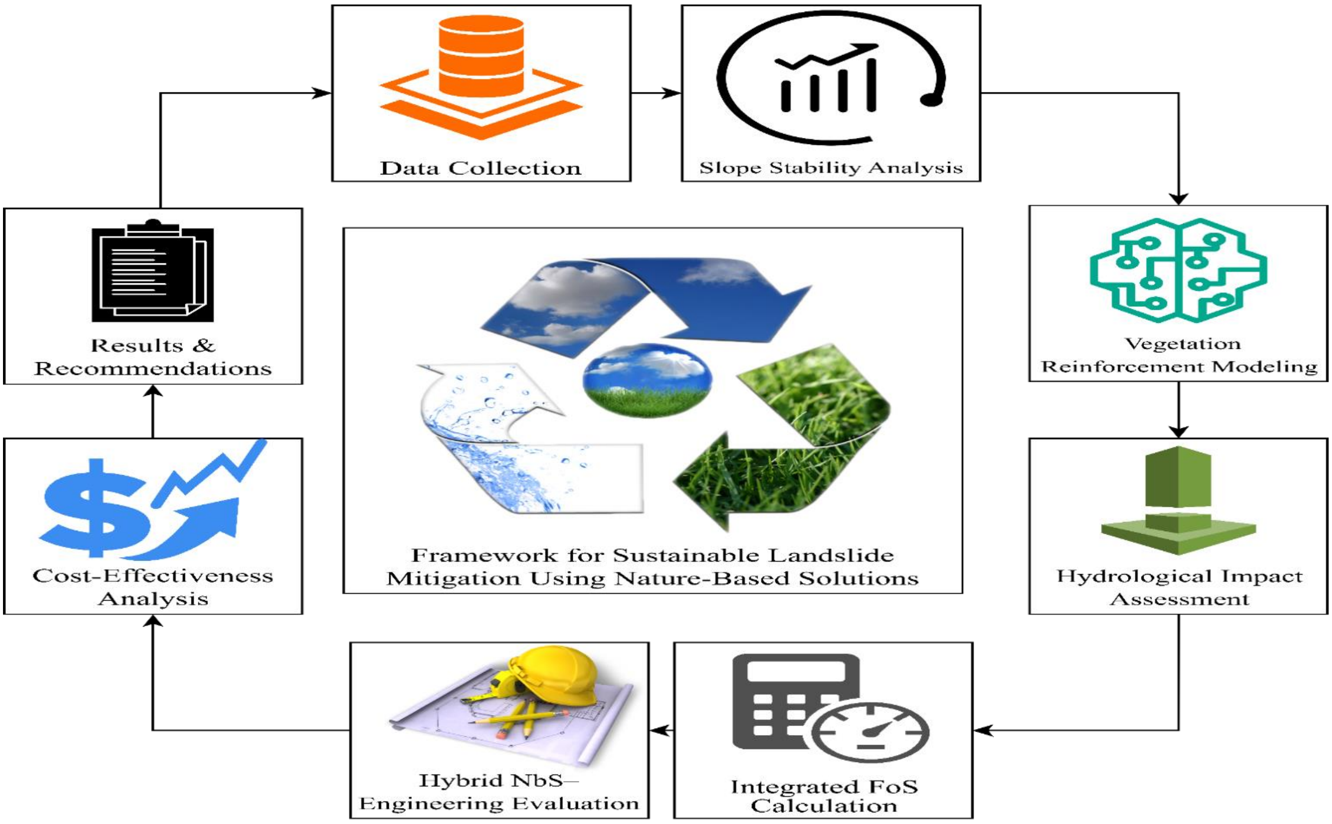

FIG. 1: FRAMEWORK FOR SUSTAINABLE LANDSLIDE MITIGATION USING NATURE-BASED SOLUTIONS

This methodology integrates geotechnical equations, vegetation root mechanics, hydrological infiltration, and cost-benefit analysis into one framework. Equations (1-10) provide the foundation for quantifying how NbS enhance slope stability. The flowchart ensures step-by-step execution, starting from raw data collection to final evaluation. By incorporating vegetation reinforcement and hydrological regulation into traditional slope stability analysis, this framework enables objective comparison of sustainable NbS against conventional engineering approaches.

IV. RESULT & DISCUSSIONS

The sustainability analysis of landslide mitigation strategies indicates that NbS offer significant advantages over conventional engineering methods in terms of cost-effectiveness, environmental resilience, and community benefits. Case studies consistently show that vegetation reinforcement and watershed restoration effectively reduce shallow landslides, though they require time to reach optimal efficiency. As illustrated in Figure 2, engineering measures provide immediate stabilization, while vegetation-based systems strengthen progressively as root networks develop. Hybrid approaches, combining engineering and NbS, deliver the most balanced results in terms of reliability, durability, and long-term sustainability.

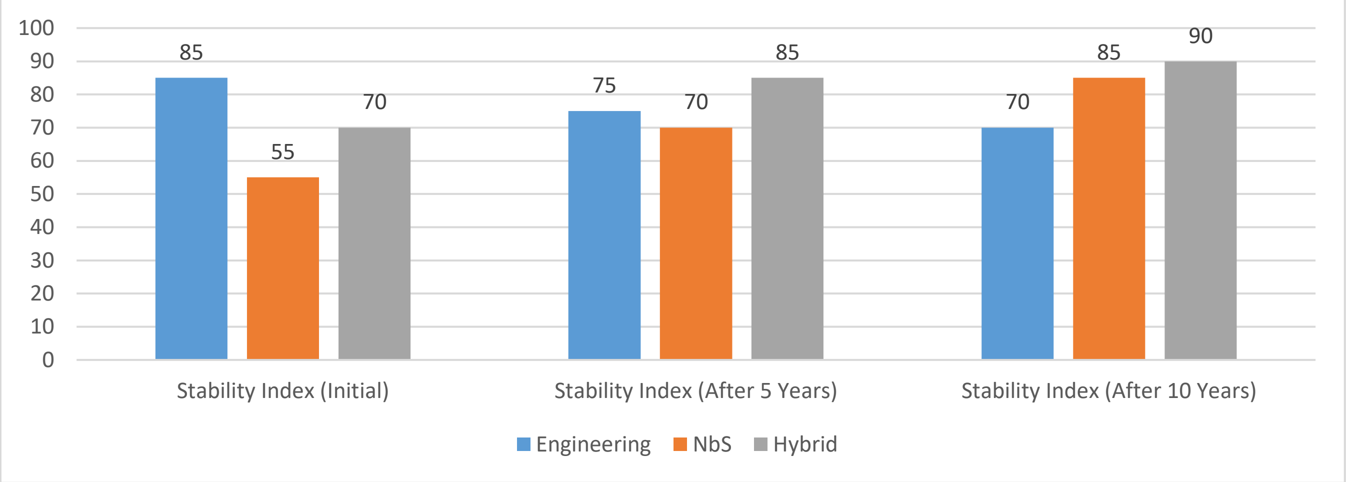

FIG. 2: COMPARATIVE SLOPE STABILITY IMPROVEMENT ACROSS APPROACHES

Nature-based landslide mitigation approaches are increasingly promoted as sustainable alternatives to conventional engineering measures. They rely on vegetation, soil bioengineering, and ecosystem-based hydrological management to reduce landslide susceptibility, particularly in shallow and erosion-prone slopes [1][4]. In contrast, engineering measures employ structural interventions such as retaining walls, rock bolts, and drainage systems, which are more suitable for large-scale and deep-seated instabilities [4][5]. To highlight the relative strengths and limitations of these two approaches, a comparative summary is presented in **Table 1**.

TABLE 1: COMPARISON BETWEEN NATURE-BASED AND ENGINEERING METHODS FOR LANDSLIDE MITIGATION (after Gray & Sotir, 1996; Morgan & Rickson, 2003; Sidle & Ochiai, 2006; Mickovski et al., 2009; Stokes et al., 2014)

Aspect	Nature-Based Methods	Engineering Methods
Definition	Use of vegetation, soil bioengineering, and natural hydrological processes to stabilize slopes and reduce landslide risk [1][4].	Use of civil engineering structures such as retaining walls, rock bolts, and drainage systems for slope stabilization [4].

Aspect	Nature-Based Methods	Engineering Methods
Techniques	Vegetative slope stabilization, reforestation, bioengineering (live check dams, brush layering, fascines), agroforestry, eco-drainage, terracing [1][2].	Retaining walls, gabions, shotcrete, rock anchors, surface and subsurface drainage, concrete check dams [4].
Effectiveness	Effective for shallow landslides, erosion control, and slope greening; improves gradually with plant growth [3][5].	Immediate and effective for both shallow and deep-seated landslides; suitable for large-scale projects [4].
Cost	Low to moderate; uses locally available materials and species [1].	High; requires heavy machinery, concrete, steel, and skilled labor [4].
Sustainability	Environmentally friendly, enhances biodiversity, provides co-benefits such as carbon sequestration and water regulation [5].	Environmentally intrusive, often alters natural landscapes and ecosystems [4].
Maintenance	Requires regular monitoring, protection from grazing, and community involvement [2].	Requires technical inspection and repair but less dependent on local community participation [4].
Suitability	Rural areas, developing regions, ecologically sensitive zones, community-driven projects [1][5].	Urban areas, critical infrastructure, high-risk zones requiring immediate stabilization [4].

Beyond slope stabilization, vegetation also plays a vital role in regulating hydrology. Afforestation and watershed restoration significantly reduce surface erosion and runoff, thereby decreasing shallow slope failures. Reduced runoff further improves water quality and controls sedimentation—benefits often absent in conventional engineering approaches. Table 2 provides a comparative overview of the performance of engineering measures and NbS in terms of slope stability, hydrological regulation, and ecological co-benefits.

TABLE 2: COMPARISON OF ENGINEERING VS NATURE-BASED APPROACHES IN LANDSLIDE MITIGATION

Criteria	Engineering Measures	Nature-Based Solutions
Slope Stability (Short-Term)	High	Moderate
Slope Stability (Long-Term)	Moderate	High
Hydrological Regulation	Low	High
Ecological Benefits	Negligible	Significant
Cost Efficiency	High initial cost	Low to moderate cost

Community participation plays a crucial role in the success of NbS. Unlike conventional engineering projects that require large financial and labor investments, NbS depend on local involvement, making them more socially acceptable and sustainable. Communities engaged in reforestation, agroforestry, or bioengineering often take responsibility for long-term maintenance, enhancing the durability and effectiveness of interventions. As illustrated in Figure 2, while engineering structures demand high initial and ongoing maintenance costs, NbS require significantly lower expenses once established, further supporting their long-term viability.

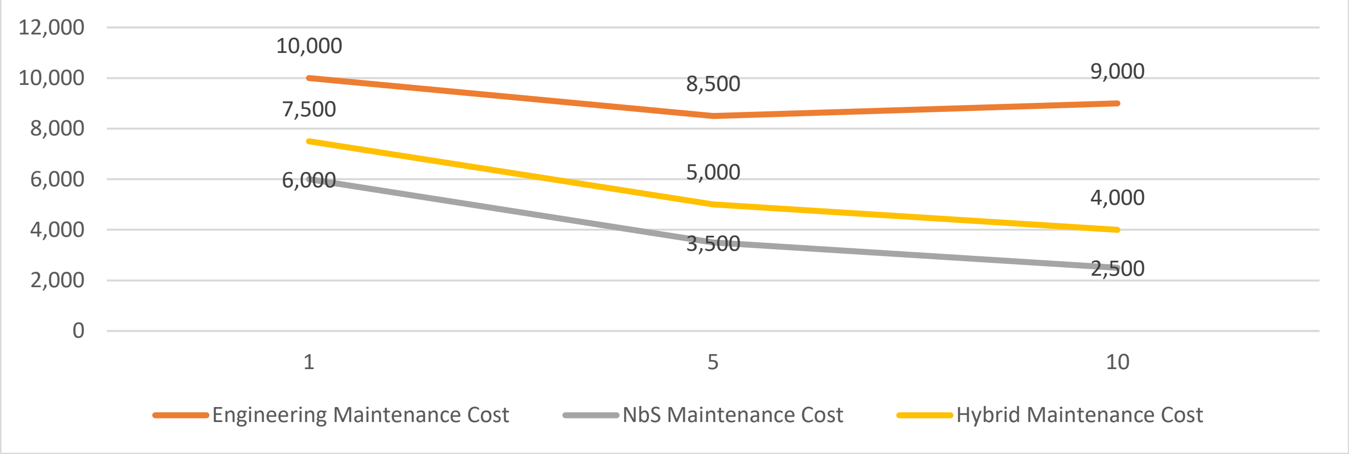

FIG. 3: MAINTENANCE COSTS OF ENGINEERING VS NBS INTERVENTIONS OVER TIME

The effectiveness of hybrid systems—combining vegetation with engineering aids such as geosynthetics or drainage structures—has proven particularly strong on critical slopes. These systems provide immediate stabilization while preserving long-term ecological processes. Case studies show that hybrid approaches experience fewer slope failures during heavy rainfall compared to purely engineered or purely ecological methods. Table 3 compares the cost-effectiveness of these strategies, illustrating the balanced investment and performance achieved through hybrid solutions.

TABLE 3: COST-EFFECTIVENESS OF DIFFERENT LANDSLIDE MITIGATION STRATEGIES

Approach	Initial Cost	Long-Term Maintenance	Co-Benefits	Overall Effectiveness
Engineering	Very High	Moderate to High	Minimal	High (short-term)
NbS	Low to Moderate	Low	High	High (long-term)
Hybrid	Moderate	Moderate	High	Very High

Analysis across diverse slope conditions shows that engineering solutions are most suitable for urban or infrastructure-dependent areas requiring immediate protection, while Nature-based Solutions (NbS) are more effective in rural and mountainous regions due to their ability to enhance soil structure and hydrological balance with fewer resources. Hybrid systems, combining short-term stability from engineering and long-term sustainability from NbS, offer the most adaptable approach for mixed land-use areas. As shown in Figure 4, the adoption of NbS and hybrid methods has steadily increased over the past decade, while reliance on purely engineering solutions has declined due to higher costs and environmental concerns.

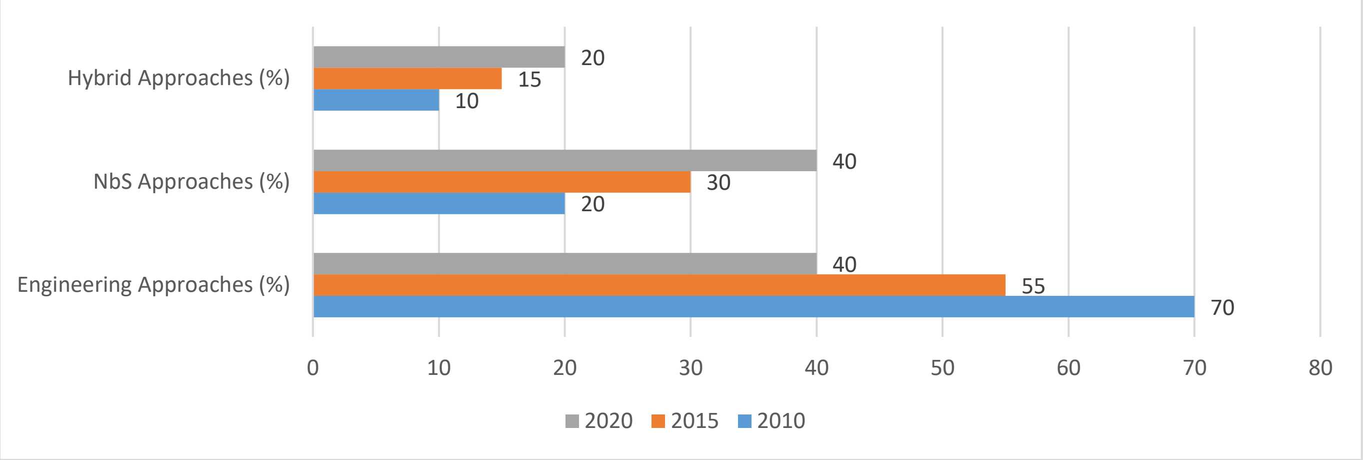

FIG. 4: ADOPTION TRENDS OF LANDSLIDE MITIGATION APPROACHES OVER THE LAST DECADE

The findings suggest that while Nature-based Solutions (NbS) may not fully replace traditional engineering in all situations, they provide a practical, sustainable, and environmentally friendly approach for enhancing long-term slope resilience. Their effectiveness is further strengthened through integration with modern monitoring technologies, supportive policies, and active community participation. Therefore, NbS should be mainstreamed into national and regional disaster risk management strategies, serving as core components for achieving sustainable and resilient slope management [11].

V. CONCLUSION

Nature-based solutions represent a sustainable and holistic approach to landslide mitigation, offering ecological, economic, and social advantages over conventional engineering measures. By employing vegetation and hydrological regulation to stabilize slopes, NBS not only reduce landslide risk but also support climate adaptation, biodiversity enhancement, and community resilience. Nonetheless, their implementation is constrained by ecological and climatic site conditions, long establishment periods, and limited standardized evaluation frameworks, which complicate cross-regional comparisons of effectiveness. Sustained maintenance and monitoring remain critical but are often neglected in practice.

Future progress should prioritize the development of hybrid strategies that combine NBS with contemporary geotechnical engineering, supported by advanced monitoring tools such as remote sensing and artificial intelligence. Establishing global standards for performance evaluation, strengthening policy support, and securing long-term funding are essential for scaling up these approaches. Equally important is fostering community participation and capacity building, which can ensure local ownership and resilience. Ultimately, NBS should be viewed not merely as a mitigation tool but as an integrated pathway toward sustainable disaster risk reduction and ecosystem-based resilience.

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