Green Infrastructure Solutions for Slope Stabilization along the Kathmandu Terai/Madhesh Fast Track Road Project

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Abstract

This paper addresses and examines slope stability issues and the potential of green infrastructure along the Kathmandu-Terai/Madhesh Fast Track (KTFT) road project in Nepal. KTFT, a strategic infrastructure endeavor, traverses through diverse terrains, including steep mountains, unstable slopes, and river gorges, posing significant slope stability risks. The slope stabilization methods using traditional civil engineering techniques frequently result in negative technical, financial, and environmental effects, although positive outcomes are also possible under certain conditions. This study highlights green infrastructure as a viable and sustainable alternative, incorporating bioengineering, terracing, and re-vegetation techniques. In addition to stabilizing slopes efficiently, green infrastructure adheres to resilience, affordability, and environmental conservation concepts. This paper conducts a slope stability analysis using Cambisols soils along the KTFT route, demonstrating the significant improvement in slope stability with the implementation of green infrastructure. However, challenges like policy gaps, limited technical expertise, and social considerations need to be addressed for successful implementation. When choosing suitable green infrastructure techniques, this study highlights the significance of taking site-specific characteristics, financial constraints, and aesthetic concerns into account. It is also emphasized that routine maintenance is necessary to guarantee the long-term viability of green infrastructure solutions. The promise of green infrastructure as a cutting-edge and environmentally friendly solution to slope stability problems that also promote environmental preservation and the long-term well-being of the area is highlighted in the paper's conclusion.

Keywords: green infrastructure, slope stabilization, Kathmandu Terai/Madhesh Fast Track, soil stability, sustainability.

Introduction

The "national pride project", Kathmandu-Terai/Madhesh Fast Track (KTFT), spanning 70.977 kilometers along with the Bagmati river corridor, is an important component of Nepal's infrastructure. Although the idea for this fast track was first conceived in 1991 and has been the subject of much discussion, the track was only opened by the Nepali Army in 2013. (Aryal & Khatiwada, 2019) The project consists of 89 bridges totaling 12.885 kilometers (about 8.01 mi) in length, with a formation width ranging from 25 to 27 meters. In addition, a total of 6 tunnels measuring 10.055 km (about 6.25 mi) in length and 5 meters in clear height and width of 11m are part of the construction. Roadside ditches, box culverts, and pipe culverts make up the drainage system. The road has an 'A' Level of Service (LOS) rating and is classified as Primary Class under the Asian Highway Design Standard 1993. The project's length is Km 0+000 in Khokana, Kathmandu, to Km 70+977 in Nijgadh, where it ends at the East-West Highway Junction. (KTFT Bulletin 2077 – Vol.1)

"Soil stabilization" refers to improving the engineering properties of the soil, making it more stable. The KTFT course crosses various landscapes, including high mountains, precarious slopes,

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and river gorges, all of which present different stability issues. Between Khokana and Nijgadh, the topography is depicted in both 2D and 3D in Figure 1. Similarly, there is a far higher risk of landslides and slope failures in Nepal as the country is located in an earthquake-prone zone. Furthermore, according to one of the studies, the area along the KTFT experiences a variety of soil types, from young, acidic, and organic-rich soil that is prone to erosion to rich alluvial soils that are perfect for farming. (Gurung, 2020). All these facets highlight the unique difficulties with slope stability along the Kathmandu Terai fast track, which, if left unchecked, may result in issues with soil erosion, landslides, and interruptions to operations and construction.

One such way to address issues with slope stability is the Green Infrastructure; In addition to promoting slope stability, green infrastructure also helps with environmental pollution reduction, storm-water management capacity enhancement, mitigation of the heat island effect, and climate change adaptation. Green infrastructure is a network of artificial and natural systems that imitate natural processes to benefit metropolitan areas on an economic, social, and environmental level. (Ying et al., 2022). For slope protection, the principles of bioengineering, terracing, and re-vegetation are all included in green infrastructure. The three main ways that vegetation protects the main slope are: the hydrologic effects of leaves and stems, root reinforcement in the soil, and ecological restoration. (Xu et al., 2019) Additionally, green infrastructure turns out to be more affordable over time because it requires lower maintenance than traditional steel and concrete systems. (Naumann et al., 2011) Therefore, using green infrastructure is a strong and forward-thinking solution for long-term slope stability. It offers complete environmental care in addition to providing protection against slope-related hazards.

This paper aims to investigate and encourage the adoption of green infrastructure alternatives to properly address the problems with slope stability along the Kathmandu-Terai/Madhesh Fast Track (KTFT) Road Project. The objectives of this research are:

1. To examine the Current Conditions for Slope Stability
2. Identify the Primary Barriers
3. Determine If Green Infrastructure Is Useful
4. Analyze the consequences for the economy and environment.

The presented analysis argues that implementing green infrastructure is an essential and long-lasting approach to solving slope stability problems along the KTFT. Using natural processes like

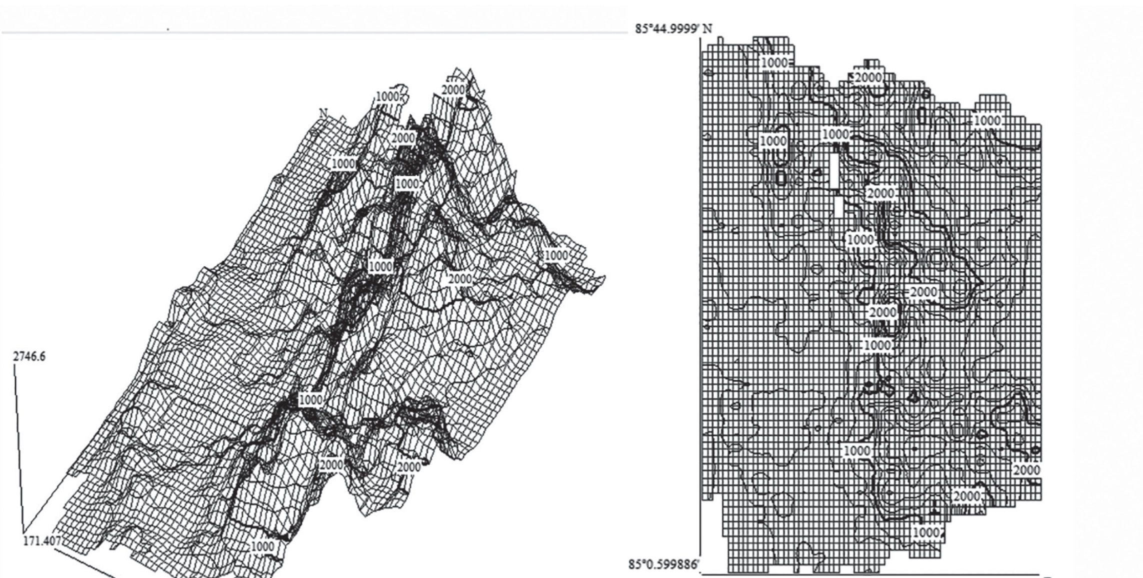

Figure 1: The 3D and 2D representation of the terrain between Khokana and Nijgadh generated using Quik Grid Software.

bioengineering, terracing, and re-vegetation, green infrastructure responds quickly to slope-related issues while upholding the objectives of resilience, economy, and environmental conservation. This paper argues that green infrastructure is more than just a way to stabilize slopes; rather, it is a progressive commitment to sustainable infrastructure development, in keeping with the broader goals of environmental stewardship in infrastructure projects.

Literature Review

In cases of extensive landslides occurring deep within the Earth, where a substantial volume of earth mass separates from the ground, diverse civil engineering techniques are employed. Altering the geometry, building retaining walls, using rock-filled buttresses, applying geotextile applications, soil nailing, sheet pile walls, gabion walls, reinforced earth walls, crib walls, contiguous bored pile walls, and implementing slope drainage measures are some of these techniques. (Pereira, B., Fernandes, W. (2023).) However, as Table 1 summarizes, these traditional methods of soil stability frequently have an adverse effect. As Nepal is a developing country with a total GDP of $40.83 billion as of 2022, and as per the Nepali Army Bulletin NRs 49.23 billion was spent till 2079/80 B.S. with 25.54% of the physical work completed, the initial cost is seen to be expensive. Thus, an alternative is also required, especially in the Kathmandu-Terai/ Madhesh Fast Track, which passes through diverse flora and fauna species.

Table 1: The aspects and the impact of the conventional soil stability practices.

Aspect	Impact
Environmental	Heavy Reliance On Hard Structures
	Loss Of Habitat
	Material Sourcing And Production
Economic	High Initial Cost
	Maintenance And Repair
	Limited Adaptability
Technical	Site-Specific Constraints
	Uncertainty And Risk
	Limited Long-Term Performance

Source: Rotaru, 2022; Sujatha, 2023

Thus, considering these drawbacks, it is crucial to investigate alternate approaches that put sustainability and effectiveness first. In this regard, green infrastructure stands out as a viable strategy, particularly for the KTFT project. Green infrastructure provides strong and long-lasting solutions that are in line with the project's environmental commitment and financial limits by utilizing the power of nature through plants, soil, and natural materials. Among the three techniques applicable to green infrastructure (bioengineering, vegetated retaining walls, and geotextiles), the selection of appropriate green infrastructure techniques for the KTFT will depend on numerous factors, including the specific slope characteristics, soil conditions, budget constraints, drainage pattern, and aesthetic considerations. A complete and long-lasting slope stabilization plan can be created by carefully weighing these variables and comprehending the benefits and drawbacks of each method. The advantages of each of the green infrastructure techniques are tabulated in Table 2:

Table 2: The advantages of each of the green infrastructure

Material	Advantages
Bioengineering	Cost-Effective
	Low Maintenance
	Environmental Benefits
Vegetated Retaining Walls	Flexible
	Reduced Heat Island Effect
	Improved Sound Attenuation
Geotextile	Reinforcement
	Enhanced Vegetation Growth
	Low Maintenance

Source: Punetha, 2019

Although Nepal does not currently have any regulations that are primarily focused on green infrastructure, several existing legislative frameworks and policies inadvertently encourage the development of such measures. In addition to promoting biodiversity conservation and sustainable use, the Nepal National Biodiversity Strategy and Action Plan (NBSAP) has included payments for REDD+ (Reducing Emissions from Deforestation and Forest Degradation) and ecosystem services.

(NBSAP, 2014). In a similar vein, the National Climate Change Policy of 2076 emphasizes cutting emissions from industry and transportation while acknowledging the importance of green infrastructure for climate change adaptation plans. However, a lack of comprehensive and targeted policies specifically promoting green infrastructure remains a gap that needs to be addressed to facilitate its widespread implementation in infrastructure projects like KTFT.

Green infrastructures, though beneficial, are not able to address every case of slope failure. In the case of low soil failure, bioengineering may stabilize the soil. However, occasionally, the impact of green infrastructure on soil stabilization could be negligible or nonexistent. Under such circumstances, stabilization can only be accomplished through the building of civil engineering structures. In certain situations, arching, grouting, bolting, and soil nailing are also carried out. Thus, green infrastructure might not always be suitable. Therefore, before determining whether green infrastructure is a practical solution, a thorough review of load capacity, space requirements, slope characteristics, and the project context should be conducted.

Constructing civil engineering structures throughout the slope for soil stabilization, however, would prove to be very costly. So, in the projects like Seti River restoration project in Pokhara, a conventional technique like concrete retaining walls was constructed along the river section to control erosion and direct water flow while bioengineering techniques like vetiver planting along with gabion walls were used to stabilize riverbank and promote vegetation growth. The retaining walls acted as a physical barrier preventing water from directly scouring the banks and causing erosion while the vetiver plants' deep and extensive root system bound the soil particles together, acting as a natural defense against the scouring force of the river, particularly important during the periods of high-water flow.

Result and Discussion

The soil found along the KTFT project is diverse. However, based on the locations the dominant soil types found are: Cambisols (found on gentle slopes and valleys along KTFT), Fluvisols (found along the riverbanks and floodplains esp. in the Terai section of KTFT), Gleysols (found in poorly drained areas with waterlogging). (Gurung, 2020). A simple analysis of how vegetation affects soil stability was carried out using an AI (Artificial Intelligence) software developed by Civil AI, entitled "Free Slope Stability Analysis". The soil taken into consideration was Cambisols. The laboratory tests to analyze the percentages of sand, silt, and clay and the Atterberg limits test to assess soil's plasticity and cohesiveness were not done. A general limit for Cambisols soil made up of 60% sand, 30% silt, and 10% clay was considered. A layer thickness of 1 meter was considered (Xu et al., 2019) The values for the unit weight of soil depend on the variability of factors like moisture content, density, and organic matter. However, the typical dry unit weight varies between 15 to 20 kN/m3 while the saturated unit weight varies between 18 to 23 kN/m3 and for this analysis, a saturated unit weight of 20.9 kN/m3 was taken. A friction angle of 30° was taken as it fell within the typical range of the Cambisols soil considered. Based on Soil Texture, Density, Organic Matter content, and mineral compositions the soil's effective cohesion was taken as 0 kPa. Based on the data from Google Earth, the slope height was taken as 3.0 meters, and the slope length was taken as 6.0 meters. The water depth was taken as 0.5 meters. The weathered rock, lying below the soil with identical properties was used in both cases. The properties of weathered rock were, Layer thickness-30 m, unit weight- 18 m, friction angle- 33°, and effective cohesion- 5kPa. Though the properties like layer thickness, unit weight, and friction angle are not significantly changed with the introduction of green infrastructure. Effective cohesion, however, significantly changes with the introduction of green infrastructure. (Norris & Greenwood, 2006). So, during the analysis of slope stability with the green infrastructure the other factors were kept the same, but the effective cohesion was changed to 1 kPa. The results are shown in Figure 2.

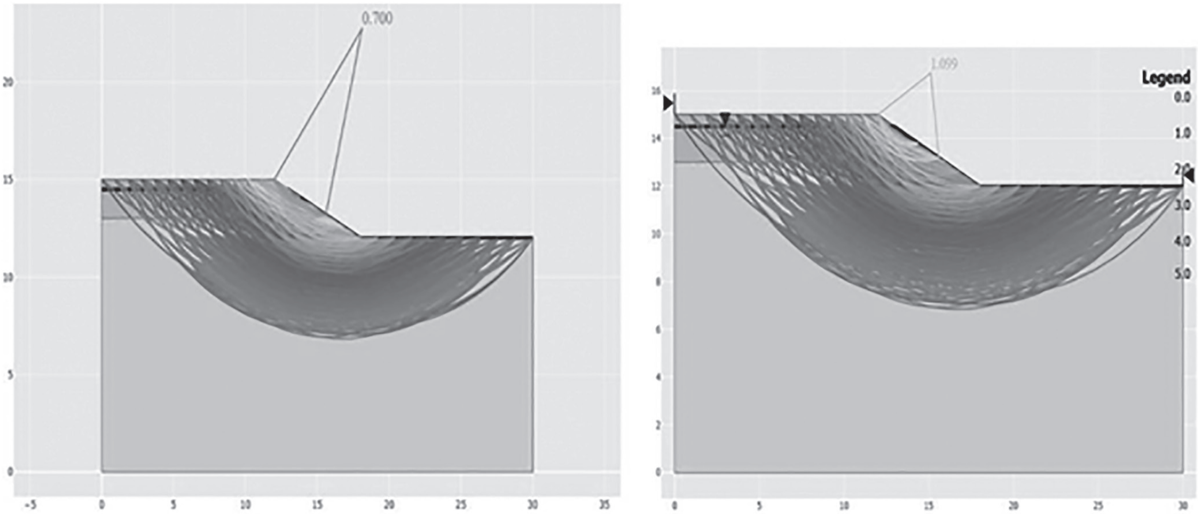

Figure 2: Slope analysis without and with Green Infrastructure created using civil AI

The result showed the critical safety factor for the slope analysis without the green infrastructure was 0.7, making the slope unstable. However, with the green infrastructure, the critical safety factor for the slope was increased to 1.1, making the slope stable. This analysis helped prove that slope stabilization is possible with the introduction of green infrastructure. However, this analysis was only done considering the long-term slope stability using effective stress properties and assuming the homogenous soil throughout. No surcharge load was applied, while in the real project, a surcharge load would be applied.

Additional slope stability assessments were carried out using Fellenius's Method (Ordinary Method of Slices) and Bishop's Simplified Method to further validate the results and offer a more thorough study. These techniques are commonly used in geotechnical engineering to evaluate slope stability and consider variables, including soil cohesiveness, friction angle, and slope geometry.

Bishop's Simplified Method: This soil stabilization technique does not disregard the moment equilibrium of individual slices, unlike other approaches. It considers the shear and normal forces acting on each slice's sides. According to Bishop's Simplified Method, the moment equilibrium of every slice is used to compute the factor of safety (Fs). The following formula is used to calculate the factor of safety in the method, which assumes circular slip surfaces:

$$Fs = \frac{\sum_{i=1}^{n}\left(c'_{\phi} L_i + W_{i\dot{\phi}} tan\phi'\right)}{\sum_{i=1}^{n} W_{i\dot{\phi}} sin\alpha_i} \quad \text{... (i)}$$

Where,

c' is the cohesion,

L_i is the length of the base of the (i^{th}) slice,

W_i is the weight of the base of the (i^{th}) slice,

ϕ' is the angle of internal friction, and

α_i is the inclination of the slip surface at the base of the (i^{th}) slice.

(Ajmera & Tiwari, 2020; Rotaru et al., 2022).

Fellenius's Method (Ordinary Method of Slices): The potential sliding mass is divided into vertical slices by the Fellenius Method. This method simplifies the calculations by assuming there are no interslice shear forces and the safety factor is calculated as the ratio of the total driving moments to the total resisting moments for each slice.

$$Fs = \frac{\sum_{i=1}^{n}\left(c'_{\phi} L_i + W_{i\dot{\phi}} tan\phi'\right)}{\sum_{i=1}^{n} W_{i\dot{\phi}} sin\theta_i} \quad \text{... (ii)}$$

Where:

θ_i is the inclination of the slip surface with respect to the horizontal (Kadakci Koca & 'Koca, 2020).

The primary difference between Bishop's Simplified Method and Fellenius's Method is Bishop's method accounts for the moment equilibrium of each slice and includes interslice forces, whereas Fellenius's method assumes no interslice forces and only considers the overall equilibrium of the sliding mass.

Further analyses that were conducted using Fellenius's Method and Bishop's Simplified Method produced results that were in line with the first analysis, supporting the beneficial effects of green infrastructure on slope stability. It should be highlighted, nonetheless, that these assessments were predicated on assumptions and generalized soil properties. Comprehensive geotechnical investigations, laboratory testing of soil samples, and sophisticated numerical modeling techniques would be needed for more precise and site-specific estimates.

Additionally, a quantitative cost-benefit analysis (B/C) contrasting the application of traditional slope stabilization techniques with green infrastructure solutions would offer insightful information for making decisions. A thorough financial analysis considering the initial investment, maintenance expenses, and possible environmental and social benefits would assist justify the adoption of green infrastructure for the KTFT project, even though it is typically seen to be more cost-effective eventually.

The Green Infrastructure has certain challenges and limitations that need to be addressed for its implementation in the KTFT project. The challenges and limitations are summarized

Table 3: The possible challenges during the implementation of the Green Infrastructure

CHALLENGES	
Policy and Regulatory Framework:	Lack of clear guidelines and standards
	Weak enforcement mechanisms
Technical & Financial Considerations	Limited technical expertise
Social and Community Concerns	Land acquisition and resettlement
	Limited awareness and participation
Project Management and Monitoring	Integration with existing infrastructure
	Monitoring and evaluation

Source: Ajmera & Tiwari, 2020

Apart from the ones mentioned, the area along the KTFT project also has a very fragile ecosystem. So, it is necessary to balance development needs along with environmental protection. So, locally available plants should be prioritized, and the species should be perennial and not annual. Similarly, organizing and carrying out green infrastructure projects in South Asia should only be started in the initial part of the rainy season, which runs from April through June or July. When planting, the slope should be damp. So, Planning and design must be finished

Table 4: The Activities related to green infrastructure maintenance.

Routine Activities	1. Site Protection	Protection against unacceptable damages that can be caused by human and animal interference
	2. Weeding	Removal of unwanted plant species
	3. Mulching	The stem and leaves of unwanted plants that have been cut are placed near the seedlings to keep it moist and cool
	4. Grass cutting	Cutting as required to encourage the development and growth of new shoots
	5. Watering	During the dry season, regular watering as per need is essential to prevent plants from drying
Recurrent Activities	6. Thinning	To decrease the density and help in forming an open canopy, allowing ground cover plants to grow better
	7. Enrichment	Addition of vegetation in between existing vegetation
	8. Repairing	Repairing and bioengineering treatment of turf, palisades, fascines

Source: Howell, 1999

before planting can start. (Development Bank, 2020). Thus, all these should also be taken into consideration before the green infrastructure project is implemented.

The green infrastructure, however, if once used would be significantly helpful if preventive measures summarized in Table 4 were used.

Conclusion

In summary, the Kathmandu-Terai/Madhesh Fast Track (KTFT) road project faces significant challenges in terms of slope stability due to its diverse topography and vulnerability to natural disasters such as landslides and earthquakes. As highlighted in the literature review, traditional soil stabilization methods have environmental, economic, and technical drawbacks, such as habitat loss, high initial costs, and limited adaptability. This study highlighted the potential of green infrastructure as a viable and sustainable alternative for slope stabilization along the KTFT. Green infrastructure incorporating biotechnology, terracing, and vegetation techniques not only effectively address slope issues, but are also consistent with the principles of cost efficiency, resilience, and environmental protection. The advantages of green infrastructure, including cost efficiency, reduced maintenance burden, and environmental benefits, make it an attractive option for long-term slope stabilization. This study conducted a slope stability analysis focusing on Cambisols soils along the KTFT route and showed that the implementation of green infrastructure significantly improves slope stability. While this analysis provides valuable insights, it is important to recognize the challenges associated with implementing green infrastructure, including policy and regulatory gaps, limitations in technical expertise, and social considerations. Balancing development needs with environmental protection and ensuring the use of locally appropriate perennial plant species are important aspects of successful green infrastructure projects. Additionally, this study recommends that factors such as soil properties, slope conditions, budget constraints, and aesthetic considerations be carefully considered when selecting a particular green infrastructure technology. This study also highlights the importance of regular and periodic maintenance activities to ensure the long-term effectiveness of green infrastructure in slope stabilization. In summary, the results of this study highlight the potential of green infrastructure as an advanced and sustainable solution to address slope stability issues along the KTFT. Through the use of green infrastructure, the project not only reduces slope risk but also demonstrates a commitment to environmental protection and contributes to the long-term well-being of the region. However, for such an approach to be successful, policymakers, technical experts, local communities, and environmentalists must work together to overcome the challenges and ensure the effective implementation of green infrastructure in large-scale infrastructure projects like KTFT. Adoption must be ensured.

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