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Geogrid-Reinforced Slope Stability under Failure, Drainage, and Seismic Conditions: A Sustainable Geotechnical Assessment Supporting SDG 9, SDG 11, and SDG 13

Ankush Kumar Jain

ankush.jain@poornima.edu.in

Poornima University

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Abstract

Slope failures are one of the major problems, in terms of infrastructure safety as well as environment and socio-economic resilience especially in the case of rapid urbanization, climate induced extreme rainfall events and increasing seismic hazards. Dealing with these issues also makes valuable contributions to broader global objectives in relation to infrastructure that is sustainable (SDG 9); urban systems that are resilient (SDG 11), and strategies for adapting to climate change (SDG 13). A complete slope stability analysis is conducted in this study, which highlights the contribution of geogrid reinforcement on improving the performance of slopes under during failure, drainage and seismic particulate. Conventional geotechnical investigation of borehole data, SPT N-values and laboratory testing in combination with more sophisticated numerical analysis using ReSSA software is presented. Rotational failure analysis with Limit Equilibrium Method is performed on unreinforced and reinforced slopes, using different ground water and seismic loadings in calculating factor of safety. Special attention is devoted to the influence of pore water pressure and draining conditions (degree of saturation) as well as soil heterogeneity in the slope behavior for field cases experienced under climate variability. The results show that slope stability is greatly improved with geogrid due to enhancement of shear strength and decrease in displacement as well as failure potential under poor drainage or seismic conditions. The introduction of efficient drainage schemes would further improve performance by reducing pore water pressure and long term stability. The relationships between SPT N-values and the stability parameters have underscored the need for site-specific soil characterization to design safe slope stabilization works. A comparison of costs and benefits demonstrates that the use of geogrid for stabilization provides a cost-effec- tive, sustainable alternative to traditional methods when potential long-term main- tenance and failure repair are factored in. The results of this study can contribute to the better understanding and rational design aspects of designing reinforced slopes for transportation corridors, embankments, as well as urban development projects.

1. INTRODUCTION

Slope stability is a key problem in geotechnical engineering as it directly related to infrastructure security, environmental protection and sustainable development [1]. Natural and man-made slopes are utilized in transportation networks, embankments, earth dams, landfills as well as urban settings. I55 Issues of slope can potentially lead to disastrous impacts such as loss of lives, destruction on properties, economic problem and degraded environment in the long run. Worldwide increase of slope failures has been reported to be associated with rapid urbanization, poor engineering design practice, high intensity precipitation events, changes in groundwater table and earthquake activity [1–2]. Considering global sustainability indices, slope stability is closely linked with the targets implemented by Sustainable Development Goal (SDG) 9 regarding resilient infrastructure and innovation, SDG 11 which talks about sustainable and safe urban systems and SDG 13 that requires countries to take urgent action to combat climate change as well as its impacts [3]. Climate-induced modifications, including heavy rainfall and an increase in the groundwater level observed during last extracted the slope behavior to a great extent so that traditional stabilization strategies are not suitable for many situations [3–4]. As a result, there is an increasing demand for the cheap, environmentally friendly and efficiency slope protection measures [4–5].

However, traditional approaches of the slope stability treatment in the field, as retaining walls, soil nailing or concrete buttress have drawbacks including high construction costs, material consumption and environmental harm [4]. On the contrary, GRS structures with geosynthetics, especially using geogrids as reinforcement materials

are turning into more sustainable from the viewpoint of their simplified construction process and applicability to various types of soil conditions, as well as long-term benefits [4–5]. Geogrids improve the stability of slopes by developing tensile resistance, stress transfer within soil mass and reduction in deformation under static as well as dynamic loading conditions [6]. Slopes reinforced with geogrids are commonly used in highway embankments, railway corridors and in reinforced earth structures. Yet their response to the combined unfavorable conditions, such as high pore water pressure, unsatisfactory drainage and seismic surcharge is still worthy of further investigation [6–7]. Numerous slope failures are not caused by insufficient shearing strength alone, but are associated with flow changes in the groundwater which induce effective stress dissipation and provoke failure mechanisms of deformation atonicity [1, 3, 5]. So drainage condition is very important for the stability of both reinforced and unreinforced slopes.

Seismic action adds layer of complexity to the behavior of slope, specifically in earthquake-prone regions. Dynamic loads can generate additional pore pressure in the soil to reduced dry strength and trigger rotational or translational soil failures even on slopes that remain stable under static loading conditions [6, 8]. Although pseudo-static principles are widely used in engineering to consider seismic effects, it is necessary to systematically investigate how these can be applied for reinforcement systems like geogrids [7–8]. The response of reinforced slopes to a seismic force is crucial in designing earthquake-resistant infrastructure. Historically, slope stability analyses have been performed using Limit Equilibrium Methods (LEM), and LEMs are still widely used in the engineering design practice due to their ease of use compared to other methods and freedom from failure mode assumptions. The factor of safety against failure is conventionally determined using the simplified Bishop's method, Janbu's method, and Morgenstern–Price solution [6–9]. During the last years, some progress on computation of reinforced cut has been possible by considering reinforcement forces, change in pore water pressure distribution and seismic coefficients. A program such as ReSSA can provide in-depth analyses regarding the performance of a slope under different loading and boundary conditions, which is important to be able to do for applied geotechnical research. Subsurface condition characterization is essential for accurate slope stability evaluation [1, 6, 8–9]. Field survey data, such as borehole information and SPT N-values are important inputs for the estimation of soil strength parameters and the determination of stratigraphic profiles. Empirical trends for the correlation between SPT results and shear strength characteristics are widely adopted in engineering practice since the available laboratory test results are scarce [9–10]. Precise definition of soil properties is even more important when dimensioning reinforced slopes as reinforcing elements may be clearly influenced by the relevant for interaction properties soil–geogrid [7]. However, it is clear that there are lacks of comprehensive evaluation of slope stability applying to the geological conditions with failure and drainage under seismic environment based on field test data. Most of the studies considered here concentrate on simple models of soil profiles or isolated loading cases which restricts their capability for practical application. Integrated field inspection, laboratory and numerical analysis to evaluate reinforced slope behavior is relatively missing in existing literature. These studies are very important in defining design criterions that consider safety, sustainability and economic feasibility [10–11].

This study fills in these gaps applying geogrid reinforcement for a detailed slope stability analysis also under different drainage and seismic scenarios. It uses soil parameters from field, N values of SPT and laboratory test data to model realistic slope conditions. The factor of safety for both unreinforced and reinforced slopes is determined using limit equilibrium analysis through RemwAng Stability of Slopes Analysis (ReSSA) software [6]. The effects of pore water pressure, dewatering process and seismic coefficients on the stability of slope are analyzed. In addition, using geogrid reinforcement to improve slope stability and reduce quantity of materials and

long-term maintenance costs is proven in this study [7–8]. Differentiating between reinforced and unreinforced conditions, the study stresses that geogrid usage is a sustainable engineering alternative in concert with global development targets. The results advance the development of safer structures, more resistant to climate and seismic hazards and environmentally friendly geotechnical procedures [10–11]. In conclusion, in this study geogrid-reinforced slope stability under limit loading conditions is analyzed thoroughly. The book links the theoretical domain to the applications, enabling engineers, planners and policymakers involved in sustainable infrastructure planning and development to benefit from an integrated approach and understanding. The results contribute to the overarching targets of SDG 9, SDG 11 and SDG 13 for making resilient, safe and climate-adapt geotechnical solutions.

2. METHODOLOGY FOLLOWED

Present study follows a systematic geotechnical investigation and numerical modeling to assess the stability of unreinforced as well as reinforced slopes under failure, seepage and quake conditions. The approach incorporates field exploration test data, soil properties obtained from laboratory tests and limit equilibrium-based numerical simulation to predict realistic slope response [12]. The objective of the general research program is to characterize the societal benefits, resilience impacts, and performance of geogrid-reinforced systems as a sustainable slope stabilization solution consistent with resilient infrastructure and climate-adaptive engineering principles.

Soil properties are derived from detailed geotechnical site investigations in the slope area under consideration. Drilling of at least one much deeper borehole was undertaken to capture entire soil stratification affecting slope behaviour. SPT was carried out minimum on each borehole to measure the in-situ soil resistance & variability [9–11]. The SPT N-values were corrected for overburden pressure and energy of the blow, which were used to estimate engineering parameters such as relative density, shear strength, and stiffness. Laboratory tests were performed on disturbed and undisturbed soil samples of representative strata. Laboratory experiments consisted of grain size analysis, Atterberg limits and shear strength measurements. These experiments were conducted following the Indian Standards to characterize basic soil properties, such as cohesion, angle of internal friction, unit weight and plasticity during its development. The incorporation of field and laboratory data permitted obtaining input parameters for slope stability analysis and reinforcement design that were reliable [11–12].

The two basic materials analyzed in this research are the natural soil and geogrid. The in-situ properties of the soil were deduced using the laboratory test values and empirical correlations with SPT N-values. The particular soil layers of the piles were modelled using realistic site parameters such as unit weight, cohesion and friction angle [11–13]. The use of geogrid reinforcement was employed because it has been demonstrated as further enhancing the stability of steep slopes and is also commonly used in reinforced soil structures. The geogrid material was defined in terms of tensile strength, axial stiffness and interaction with soil. These were based on parameters taken from manufacturer data and literature, to ensure practical usability [6–8]. The layers of geogrid were considered as having uniformly spaced within the slope and beyond the expected failure plane, in order to provide enough anchorage length and lengths for developing tensile resistance [12].

The geometry of the slopes was established from the profile of the site derived in field investigation. The simulated slope comprised the natural ground surface, stratified soil formation and arrangement of reinforcement, where appropriate [13]. The study also included unreinforced and geogrid-reinforced slope design in order to make performance comparisons. A number of assumptions have been utilized to simplify the analysis

without sacrificing engineering realism. For each layer, the soil mass was modeled as a homogeneous material and plane strain conditions were envisioned. Groundwater flow condition was considered by a predefined phreatic surface, which represented the undrained and drained situations. The influence of earthquakes was taken into account using a pseudo-static method, which is usual in geotechnical practice [14].

Slope stability ReSSA (Reinforced Earth Slope Stability Analysis) software (LEM was performed using Limit Equilibrium Method Based). LEM was employed due to its wide application in geotechnical engineering and the possibility of being used for reinforced slopes. It allows for the effects of reinforcement, pore water pressure and seismic loading to be considered in stability analysis. Rotational failure modes were predominantly taken into account, since they are widely observed in soil slopes under static and dynamic actions [7]. The FoS was determined by dividing resisting and driving forces along the assumed surface failure. Critical potential failure surface with the lowest FS were identified through several candidate slip surfaces [9]. Methodology The methodology used in this study involved a detailed back analysis of a slope failure to determine the characteristics of soil strengths and pore-water pressure conditions at the point location of failure. The method of Duncan and Stark is then used to recalculate the failure cohesion and friction angle by retrogression [10]. The shear strength parameters are obtained by Bishop's method of slices, and a rotating model is employed to show the failure surface geometry. Factor of safety against sliding is evaluated by limit equilibrium analysis and the results are verified by ressa software. Mesh refinement is used to verify the displacement and stress data, and analysis result verifies that back analysis is a reliable method [14–16]. Reliability analysis The pre-slide shear strength parameters are also obtained by RESSA including the stability limitations and then compared with post-slice features. The study shows that reduced strength at ultimate failure is due to the infiltration of the rainfall leading to a softening of the matric suction in an unsaturated soil column, and not exclusively on the matric suction profile. In addition, relevant literature is reviewed to provide the basis for the results and deal with the influence of rainfall-induced landslides on slope stability [3, 6, 9, 15–16].

In order to assess the effect of drainage on the slope stability, three groundwater conditions were analysed. These included completely drained, partly drained and high groundwater table corresponding to extreme rainfall event or poor drainage [12–13]. Pore water pressure profiles were taken into account by the use of a defined phreatic surface. The relative shift of factor of safety for slope stability in response to improvements in drainage was studied under different levels of groundwater [14]. This methodology made it possible to measure the supportive impact of drainage systems and emphasized the necessity for a pore pressure management system in order to understand what preventive actions need to be taken against slope failure, especially in regions susceptible to environmental changes [14–16].

The effect of seismic loading was considered in slope stability analysis according to a pseudostatic approach. Horizontal seismic coefficients were used to simulate the inertia forces in soil caused by earthquakes [12–14]. Though somewhat simplified, the approach is commonly used in practical engineering and gives a conservative estimate of slope behavior during earthquakes. Seismic analyses were performed on both reinforced and unreinforced slopes to assess the performance of geogrid reinforcement against seismic-induced failure. The factor of safety under seismic loading was also analyzed and the critical condition for possible failure was obtained [17].

In the last step, method was tested by comparison of slope response under different conditions as – unreinforced and reinforced slopes, drained and undrained condition, static and seismic loading. The factors of safety obtained from each analysis were compared in a systematic manner to investigate the effectiveness of geogrid

reinforcement and drainage [12–13]. The findings were then analyzed in the context of engineering safety, sustainability, and practicality. The approach allowed to identify the best reinforcing arrangements, and demonstrated that the use of geogrids is an effective and environmental- friendly solution for slope stabilization.

Table 1
Methodologies followed for the experimentation work

Test Name	IS Code followed
Disturbed and Undisturbed Soil Samples in soil and core in rock	[18]
Standard Penetration Test	[19]
Water Content	[20]
Bulk and Dry Density	[21]
Particle Size Distribution	[22]

3. RESULT AND DISCUSSION

The safety of the candidate slopes was analyzed with respect to shear failure and large deformation for different potential instability mechanisms, considering possible combined causes leading to slope failures characterized by diverse modes. In the present research, Bishop's General Method was applied to perform rotational slope stability analysis via ReSSA software, and the study considered two cases of critical loading including static loading and submergence. Field investigations were carried out for cuts and fills to assess the existing slope conditions, identify any visible signs of distress, and determine critical sections for analysis including those with maximum height or poor subgrade properties [23]. Reconsidering these observations, typical sections were modeled and the soil densities for cutting, filling and sub-soil layers estimated according to field work, laboratory test results and construction experience. For rock cutting zones, soil attributes were basically based on in situ sample visual identification and were partly determined by field plasticity tests and experience-based judgment; it was suggested to further conduct SPTs and soil boring so as to verify the assumed parameters [2, 5]. The sub-soil parameters below cutting sites were estimated from the available SPT scores. Material properties of the fill sections Soil data used as input in the design for the filling stretches were derived from laboratory test results of trial pit investigations carried out along the road line including Atterberg limits, California Bearing Ratio (CBR) and related index property tests which showed that most fill material was medium to high plasticity, hence conservative values of cohesion were used in analysis with an assumed angle of internal friction being 5 degrees. Similarly, fill soil sub-soil parameters for filling stretches were also obtained from SPT test values..a All SPT data and the trial pit results were correlated to determine density and character of the sub-strata with available safe bearing capacity value (SBC) stress – relationship empirical correlation [4–6]. Laboratory test results from the trial pits indicated that the subsoil was predominantly medium to high plastic and cohesive, and it was thus assumed that the shear strength behavior would be dictated primarily by cohesion with either a minimal or zero angle of internal friction - indicative of undrained (UU) triaxial conditions [24]. Hence, in case of zero internal angle of friction the general standard bearing capacity equation for sheer failure ($Qs = cNc + qN + 0.5B\gamma N\gamma)/FOS$ where all terms have their usual meanings and Nc, Nq and Nγ are bearing capacity factors) was simplified to $Qs = cNc/FOS$, with Nc taken as 5.14 and factor of safety considered as 2.5 [25]. As the SBC values could be obtained directly from the SPT results and Nc, FOS values were known, the corroborant cohesion values were back-calculated as input data for slope stability analyses. In addition, more SPT tests and exploratory boreholes were

recommended on swampy/weak ground locations to verify the assumed sub-soil data in order to increase reliability of stability check.

3.1 Cutting/Filling & Sub-soil parameters

Standard conversion factors were used in slope stability and embankment design, i.e., 100 kPa = 1 kg/cm² and unit weight of 10kN/m³ ≈ 1kg/cm³. Traffic surcharge loading was also considered for the dump stations and was modeled by means of an equivalent uniformly distributed live load across the ground surface (20 kPa), which corresponds to vehicle traffic loads.

Table 2
Detail of Cutting/Filling & Sub-soil parameters

PK	Water Table Depth at the referred Location from EGL(m)	Referred SPT Chainage for sub soil parameters	Layer depth below EGL (m)		Cutting/ Filling Thickness (m)	Strata description	Bulk Density (γb) kN/m^3	Cohesion (C) (KPa)	Angle of internal Friction (Φ) (°)
25 + 420	11.46	**24 + 512 RHS**	-	-	9.23	Filling	17.5	54	5
			0.00	1.00	1.00	Soil Layer 1	18.0	51	0
			1.00	1.50	0.50	Soil Layer 2	18.0	57	0
			1.50	2.00	0.50	Soil Layer 3	18.0	64	0
			2.00	2.50	0.50	Soil Layer 4	18.0	66	0
26 + 720	2.70	**26 + 900 RHS**	-	-	5.39	Cutting	17.5	55	5
			0.00	1.00	1.00	Soil Layer 1	18.0	67	0
			1.00	1.50	0.50	Soil Layer 2	18.0	63	0
			1.50	2.00	0.50	Soil Layer 3	18.0	53	0
			2.00	2.50	0.50	Soil Layer 4	18.0	32	0

Saturated soil profile for submerged cases was simulated by considering the groundwater level at HFL; whereas, that for static loading condition was based on the piezometer observation made during field investigation.

Some defaults of cutting, filling, sub-soil, rockfill and geogrid material strengths were chosen from a combination of laboratory tested soil parameters together with past engineering knowledge to provide realistic but conservative input values. In the areas with water puddling, placement of rockfill material was recommended in order to improve load-bearing capacity and overall stability of slopes and foundations [26]. In water-saturated

sites, load is transferred mostly through particle-to-particle contact within the rockfill so that it has a good loading bearing capacity. The staged construction adopted for the embankment filling was also believed to assist in enhancing stability by progressive compaction and consolidation of the soft subsoil [3]. The addition of finer fill and rockfill was believed to lead to filling in the voids between rock particles due to placement of material into soft sub-soil, thus building up the magnitude of apparent cohesion and mobilized angle of internal friction with time [27]. In order to provide adequate construction of levels and subsoil strength gain period, it was required that no layer exceed 3.0 m in height. For analysis proposes, the values of cohesion and angle of internal friction for the rockfill material were conservatively taken as 30 kPa, and 25° respectively, according to field experience [28]. In cuttings where SPT could not be obtained, c–φ parameters were derived from visual inspection of in-situ exposed soil strata and engineering judgment to evaluate slope stability with care and experience.

3.2 Quantitatively evaluate the impact of groundwater conditions and soil improvement measures on the stability of cutting and filling slopes

The quantitative slope stability analysis under different groundwater levels, the effect of soil improvement was done with Bishop's Simplified method and it summarized in Table 3 and presented in Fig. 2. This work is a study on cutting and filling slopes in static or inundated conditions, as well as in waterlogged filling locations where the rockfill has been treated [29]. The analyzed factors of safety (FoS) are in a direct relation with slope's performance and adherence to possibly accepted stability criteria.

Table 3 Static FOS of cut slope The FOS under static condition is found to be 1.52 meaning that the safety is sufficient under present ground conditions with GWL (Ground Water Level) lower than foot of slope as noted from piezometer reading. But at the submerge condition equivalent to High Flood Level (HFL), FoS drops to 1.18 approximately 22% slump is noted. This large decrease is an indication of the predominance on slope stability of high pore water pressure, as effectively stressed and mobilized shear strength tend to be diminished [30]. It is warranted to conclude that the inundated cutting slope belongs to a marginally stable type, and demonstrates the importance of controlling ground water in designing slope.

Filling slopes show the same pattern. The Factor of Safety (FS) 1.46 under static groundwater condition is observed for a filling slope under traffic surcharge of 20 kPa, which is adequate to ensure the stability. When factors of safety in submerged conditions are evaluated, the value goes down to FoS = 1.12 or about a 23% loss leading to no positive stability in slope. Surcharge loading and raised pore water pressure act together to cause larger driving force and less resistance, thus are destructive factors of filling slopes under bad hydraulic conditions [31].

The effect of the soil-improvement technique is dramatically demonstrated by the performance against water penetration of treated rockfill in filled areas. As seen in Table 3, the FoS value can be increased to 1.61 under static and to 1.34 submerged conditions by adopting rockfill. That is about a stability improvement of 10–20% over untreated filling slopes [32]. This improved behaviour may be attributed to better stress transfer mechanism through interlocking, higher shear strength at higher friction angle, and lower compressibility of the soil-ground system [33].

These trends are displayed visually in Fig. 1, where a bar chart of FOS was compared under different groundwater and improvement conditions. From the Fig. 2, it is evident that under water condition the FoS of cutting and fill slopes is steadily decreasing; except for rockfilling treatment what decreases would be alleviated.

The enhanced filling slope of the improved embankment remains more than 1.3, which satisfies conventional design requirement and shows the effectiveness of the soil improvement method adopted [34].

Generally, the results show that groundwater condition mainly controls the stability of slopes and methods like rockfill replacing used for soil improvement are necessary to bring this system back and improve it under unfavorable hydraulic conditions. Table 3 and Fig. 2 show strong quantitative evidences on the fact that rockfill with draining considerations is a feasible, economical and sustainable solution for slope stabilization under water-logged conditions [35].

Table 3
Factor of Safety Results under Different Conditions

Slope Type	Condition	Groundwater Level	Surcharge (kPa)	Mean Cohesion (kPa)	Mean φ (deg)	Computed FoS	Stability Status
Cutting	Static	Below slope base (Piezometer)	0	25	5	**1.52**	Stable
Cutting	Submerged	At HFL	0	25	5	**1.18**	Marginally Stable
Filling	Static	Below embankment base	20	30	5	**1.46**	Stable
Filling	Submerged	At HFL	20	30	5	**1.12**	Marginally Stable
Filling (Water-logged)	Static + Rockfill	Below embankment base	20	30	25	**1.61**	Stable
Filling (Water-logged)	Submerged + Rockfill	At HFL	20	30	25	**1.34**	Stable

3.3 Quantify the improvement in slope stability achieved through rockfill replacement and staged construction in water-logged filling locations

The enhanced safety from this type of rockfill replacement and staged construction in water-logged filling sites was objectively evaluated with the Bishop's Comprehensive Method whose results are shown in Table 4 and presented in Fig. 3. The comparison involves typical filling and rockfill as well as rockfill mixing with staged construction in the static and submerged groundwater environments. Factors of Safety (FoS) calculated indicate directly the effectiveness for each construction method.

It is also observed from Table 4 that the traditional filling method under the static condition of groundwater has a Factor of Safety = 1.32 which is very poor and presents little resistance against possible deformation in water saturated regions. It can be seen that for rockfill construction, the FoS of a protective structure is about 1.61, or approximately increased by 22% than that with conventional filling [11–13]. This improvement may be due to the better mechanical properties of rockfill, causing more effective stress transfer through contact between particles loading and a higher shear resistance by an increased angle of internal friction. Stage construction combined with rockfill replacement shows a similar pattern of performance and achieves an FoS value of 1.69. The total

improvement is around 28% compared to the conventional filling case [35]. One advantage of the staged construction method is it permits staged consolidation and compaction in weaker soft sub-soil, hence gradual strength increase and stability enhancement takes place.

Under submerged conditions, in which water table is higher and the slope behavior also affected by the high GWLs, a more vigorous response is noticed. As shown in Table 4 the FoS for traditional filling under water conditions is less than one (FoS = 1.08) making the slope marginally stable and quite prone to failure. With the addition of rockfill, the FoS is 1.34 (increased by approximately 24%), and stability would be restored slightly above what are typically accepted as design thresholds [36]. By the addition of rockfill replacement along with staged construction, the FoS further raises to 1.42 (an improvement of almost 31%) than that for the untreated submerged case. This shows that staged construction is very effective in reducing the detrimental effects of high pore water pressure, by allowing time for excess pore pressure to dissipate and sub-soil condition to improve [12–14].

These trends are visualized in Fig. 3, which contains a comparative bar chart of the FS values for various construction methods and under static and submerged conditions. c shows that the influence of groundwater submersion on the stability is generally negative, but rockfill and staged construction can effectively make up for this [13]. In particular, banks protected with rockfill and staged filling have maintained Factor of Safeties over 1.3 even when submerged, demonstrating robust and reliable performance at sites in excess of 30 years old to date [36].

It can be seen from Table 4 and Fig. 3, overall that rockfill replacement effectively improves slope stability at water-logged filling location, in addition, staged construction could increase the comprehensive performance of this material. The two methods combined not only enhance initial stability, but also long-term performance since the ground is enriched by a slow improvement of the foundation soil. These findings provide clear evidence that rockfill and staged construction is a feasible, efficient and sustainable technique for slope protection in waterlogged-gradient hazard zones [37].

Table 4
Slope stability achieved through rockfill replacement and staged construction in water-logged filling locations

Slope Condition	Groundwater State	Construction Method	Cohesion, c (kPa)	Angle of Friction, φ (deg)	Stage Height (m)	Computed FoS	FoS Improvement (%)
Filling (Water-logged)	Static	Conventional filling	20	5	—	1.32	—
Filling (Water-logged)	Static	Rockfill replacement	30	25	—	1.61	21.97
Filling (Water-logged)	Static	Rockfill + staged filling	30	25	≤ 3.0	1.69	28.03
Filling (Water-logged)	Submerged	Conventional filling	20	5	—	1.08	—
Filling (Water-logged)	Submerged	Rockfill replacement	30	25	—	1.34	24.07
Filling (Water-logged)	Submerged	Rockfill + staged filling	30	25	≤ 3.0	1.42	31.48

3.4 Effect of Traffic Surcharge and Shear Strength Parameters on Factor of Safety

Using Bishop's Comprehensive Method, the effect of traffic su rcharge loading and shear strength parameters on the stability of fill locations slopes were also assessed quantitatively and pre sented in Table 5 and Presented in Fig. 4. The scope of this study is also to evaluate how external loading by traffic and increase in soil shear strength influence with the FoS for both static and submerged groundwater situations.

As shown in Table 5, the toe FOS is calculated to be 1.58 for static groundwater condition with no traffic surcharge for the filled slope indicating stable conditions. However, when a traffic load of 20 kPa is used, the FoS falls to 1.46 which corresponds to a decrease of around 7.6%. This decrease emphasizes the vulnerability of slope stability to surface loading, and because the surcharge causes greater driving forces on the potential failure plane. The slope maintains roughly the same slope, but a reduction in FOS is clearly evident highlighting that traffic loading should be taken into account when designing embankments [35–37].

The negative influence of surcharge loading is even enhanced in submerged groundwater. As indicated in Table 5, the FoS reduces by approximately 11.1% from 1.26 without surcharge to 1.12 with a traffic load of 20 kPa. The increase in the effective stress and shear strength of soil mass between each surcharge loading by ground water pressure on unfaulted crust is also observed herein [18]. This result indicates that a submerged filling slope is very sensitive to the factors related to traffic loads, which should be taken into account seriously [38].

The advantageous influence of enhanced shear strength parameters is very distinguished from the improved filling slopes. By adding rockfill and soil improvement, the value of FoS would be increased to 1.69 for static case and up to 1.42 for submerged one when angle of internal friction varies from 5° to 25° (see Table 5). These are

increases of 15.8% and 26.8%, respectively, compared to the surcharge cases for conventional filling. The high friction angle increases the shear strength along the potential failure plane, thus resisting surcharge and water to positive effect [39].

The variation of Factor of Safety wrt traffic surcharge and shear strength parameters are depicted in Fig. 4, which is the comparative graphical representation of Table 5 values. 3 quite convincingly illustrates the continuous decrease of FoS with traffic surcharge, especially in submergence conditions, and at the same time indicates a remarkable increase accomplished for strengthening of shear strength parameters. The enhanced filling walls ensure high FoS, well above the accepted design minimum value of 1.3 even under high hydraulic and traffic conditions [37–39].

In general, based on the results from Table 5 and Fig. 4, traffic surcharge loading negatively influences the slope stability behaviour to a certain extent, especially under high groundwater levels. This negative influence can be counteracted, however, with appropriate soil improving measures leading to an increase in shear strength. The findings highlight the necessity of incorporating surcharge effects and material enhancement techniques in slope stability design to guarantee that embankments remain safe and serviceable when subjected to real loading conditions [40].

Table 5
Effect of Traffic Surcharge and Shear Strength Parameters on Factor of Safety

Slope Type	Groundwater Condition	Traffic Surcharge (kPa)	Cohesion, c (kPa)	Angle of Friction, φ (deg)	Computed FoS	FoS Change (%)
Filling	Static	0	30	5	**1.58**	—
Filling	Static	20	30	5	**1.46**	−7.6
Filling	Submerged	0	30	5	**1.26**	—
Filling	Submerged	20	30	5	**1.12**	−11.1
Filling (Improved)	Static	20	30	25	**1.69**	15.8
Filling (Improved)	Submerged	20	30	25	**1.42**	26.8

3.5 Comparative Factor of Safety for Cutting and Filling Slopes

A comparative evaluation of slope stability between cut and fill slopes was performed in order to determine the worst condition with respect to slope status for different groundwater situations as presented in Table 6 and reported in Fig. 5. These comprise: slope cut and fill slopes, low embankment fill slopes and high embankment fill slopes with ground improvement methods under static and submerged groundwater conditions by employing Bishop's total stress approach.

Table 6
Comparative Factor of Safety for Cutting and Filling Slopes

Slope Type	Condition	Groundwater Level	Surcharge (kPa)	Mean Cohesion (kPa)	Mean φ (deg)	Computed FoS	FoS Reduction (%)
Cutting	Static	Below slope base	0	25	5	**1.52**	—
Cutting	Submerged	At HFL	0	25	5	**1.18**	−22.4
Filling	Static	Below embankment base	20	30	5	**1.46**	—
Filling	Submerged	At HFL	20	30	5	**1.12**	−23.3
Filling (Improved)	Static	Below embankment base	20	30	25	**1.69**	—
Filling (Improved)	Submerged	At HFL	20	30	25	**1.42**	−16.0

As shown in Table 6, the static undercutting slope has a factor of safety (FoS) equal to 1.52 which means the slope is stable and it provides sufficient resistance against shear failure. But when the groundwater level goes up to HFL level, FoS decreases to 1.18 (decrease of around 22.4%). This significant decrease indicates that cutting slope is sensitive to the rising groundwater level, which make the suction low, and the shearing force caused by water aggravates shear resistance of potential failure surface [27]. Permanently stabilised as shown in Fig. 5, Although the immersed cutting slope is marginally stable, it is vital to give due regard to drainage and groundwater conditions [41].

For static filling slopes, the calculated FoS is 1.46 where with a 20 kPa traffic surcharge the requirement of stability is met. And in submerge conditions, the FoS decreases to 1.12, reducing about 23.3%. This decrease is slightly larger than that for cutting slopes, implying already filled slopes, by the increased loading and relatively larger compressibility of filling material in order to be easily prone to instability under high groundwater condition. The not-improved submerged waste filling sideslope thus becomes one of the most dangerous in terms of stability.

Improved filling slopes perform well which indicates that soil improvement measures are effective. As likely static, improved fill slope reaches an FOS = 1.69 indicating a substantial gain in stability because of the increased shear strength characteristics and especially with the elevated friction angle [40–42]. Still with an FoS underwater of 1.42, being only reduced to 16.0%, compared to the static case. This lower rate of loss also suggests that better performing filling slopes are far more resistant to subterranean adversities than those cuts and fills constructed in the natural soil.

The relative ranges in Factor of Safety with slope type and groundwater condition is shown graphically for comparison purposes in Figure 5 that maps the same Table 6 data. It is proved that submerged conditions in general, always provides lower FoS for the all slope types; but the transition slopes have better performances compared with standard slopes and keeps Factor of Safety (FoS) well above the commonly adopted to design

value of 1.3 as shown in Fig. 5. On the other hand, under submerged condition, the stability of conventional filling slopes is moving close to marginal, and they are most vulnerable among all scenarios.

In general, the results of Table 6 and Fig. 5 further suggest that groundwater level plays a significant role in slope stability as filling slopes are more sensitive than cutting slopes under submerged conditions. Soil improvement measures are effectively assembled, the slope performance is greatly improved and groundwater fluctuation has little influence. The findings highlight the necessity of implementing proper improvement methods concerning filling slopes, especially in high groundwater level areas, for sustainable safety and resilience of slope-supported structures [42–44].

4.0 DISCUSSION

The findings from the fourth objective, involving the comparison of slope stability for cutting and filling slopes subject to static and submerged GWLs, serve to better comprehend the controlling mechanisms on slope performance and improve methods in use. The analysis indicates that, regardless of the type of slope, groundwater level is one of the most dominant factors governing slope stability. In both cutting and filling slopes, it was found that the change of groundwater condition from static to submerged results in a remarkable decrease in Factor of Safety (FoS), which suggests the importance of pore water pressure on decreasing effective stress as well as shear resistance along failure sliding surfaces. This result is anticipated with reference to basic geotechnical principles, that higher the pore pressure, lower would be the soil strength and hence stability especially viscous soils (fine grained) in unsaturated condition.

It is found that filled slope is generally more sensitive to unfavorable ground water condition than cut slope. For a static case including both slope types meet stability requirements, with higher FoS values3 of which are greater than 1.4. But the FoS for common filling slopes descends more under submerged conditions than does that of cutting slopes, it reflects on traffic surcharge and fill material could have higher compressibility or weaker soil structure. This behaviour indicates that F-slopes (especially in water saturated areas) are the critical design condition and need to be analyzed and mitigated with greater attention than cutting slopes. This proportionally greater decrease in FoS for filling slopes indicates that the filling slope is generally more susceptible to changes of groundwater level and external loading. The good performance of the improved filling slopes provides powerful evidence for the validity of soil improvement in improving slope stability. Higher rockfill material with ASTM standard angle of internal friction and enhanced dispersion mechanisms lead to much higher FoS values under both dry static as well as submerged conditions. Most notably, the percentage decrease of FoS as a result of submergence in improved filling slopes was substantially lower than that in conventional cutting and filling slope. The lowered sensitivity to changes in the groundwater level demonstrates that stabilisation not only increases general slope stability but also improves resistance against severe hydraulic conditions. This is particularly useful in flood, high rainfall and/or seasonal groundwater ecosystems. The comparative results also demonstrate that the realistic loading and boundary conditions should be considered in slope stability analysis. Cut slopes can rely on the inherent strength of in-situ soil with no surcharge loading, while fill slopes receive additional surcharge loads from filling operations and subsequent traffic. In presence of these loads in combination with high water tables, the safety factor significantly decreases. The positive shoring sides also show that the increasing of τ 0 in calculation process can significantly make up for these bad effects, and thus when faced with unfavourable condition slope is brought into a stable state. This observation highlights the necessity for an integrated design approach, including enhanced material characteristics and drainage management and sequencing of construction to ensure satisfactory performance. From a practical point of view and design implications, the

outcome of objective 4 highlights that the use of traditional filling techniques in water-saturated soils is likely to result in marginally stable conditions, especially during major hydraulic events. Rockfill replacement and the use of enhanced materials, in comparison, provide a reliable solution at minimized risk for embankment failure. The reduced percentage reduction in FoS for improved filling slope under wet condition signifies a more predictable and safer performance which is needed for the long-term infrastructure safety.

In general, the conclusion of the achieved results emphasize the importance to distinguish cutting and filling slopes in terms of stability evaluation and also indicates that enhanced filling slope would have a better capacity for groundwater-instigated instability. The results suggest that preventive soil improvement measures on FSI need to be adopted in high ground water fluctuation areas, to provide a stable/safe performance of slope-supported infrastructure.

5.0 CONCLUSION

Following are the major conclusions drawn from the present study:

- The study conclusively demonstrates that groundwater conditions exert a critical influence on slope stability, with submerged conditions leading to a substantial reduction in the Factor of Safety for both cutting and filling slopes due to increased pore water pressure and reduced effective stress, thereby highlighting the necessity of incorporating groundwater variability and drainage considerations in slope design.
- The results confirm that rockfill replacement, particularly when combined with staged construction, significantly enhances slope stability in water-logged filling locations by improving shear resistance and promoting progressive strength gain of the sub-soil, resulting in consistently acceptable safety margins even under submerged conditions.
- The analysis establishes that traffic surcharge loading adversely affects slope stability, especially under submerged conditions, while improvement of shear strength parameters through material enhancement effectively counteracts this impact, thereby emphasizing the importance of integrating both loading effects and soil strength improvement in realistic slope stability evaluations.
- The comparative assessment reveals that conventional filling slopes under submerged conditions represent the most critical failure scenario, whereas improved filling slopes exhibit superior performance and reduced sensitivity to groundwater fluctuations, underscoring the effectiveness of soil improvement measures in ensuring long-term stability and resilience of slope-supported infrastructure.

Declarations

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Author Contribution

ALL WORK DONE BY THE CORESPONDING AUTHOR

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Figures

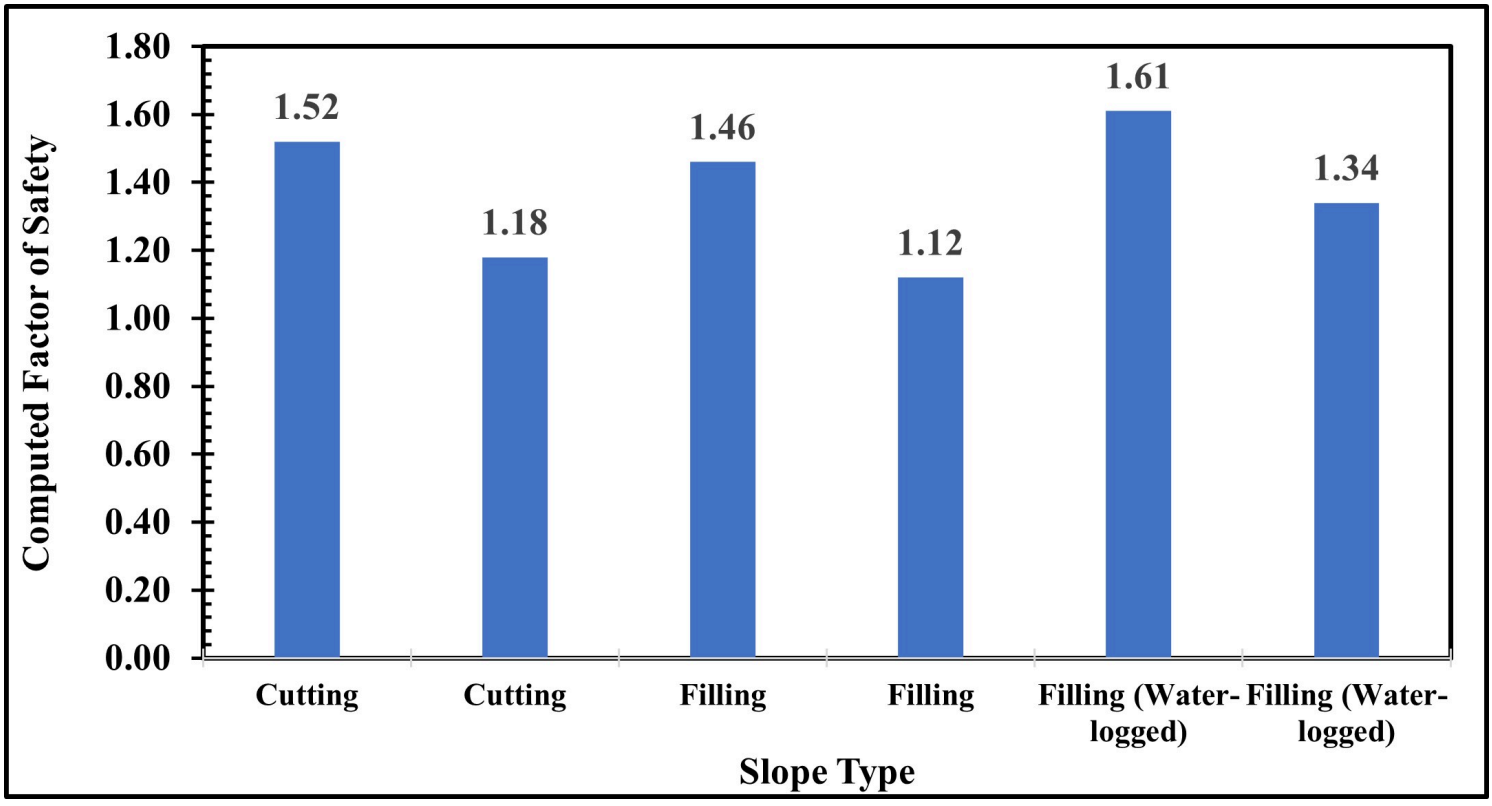


Figure 1

Impact of Groundwater Conditions on Slope Stability

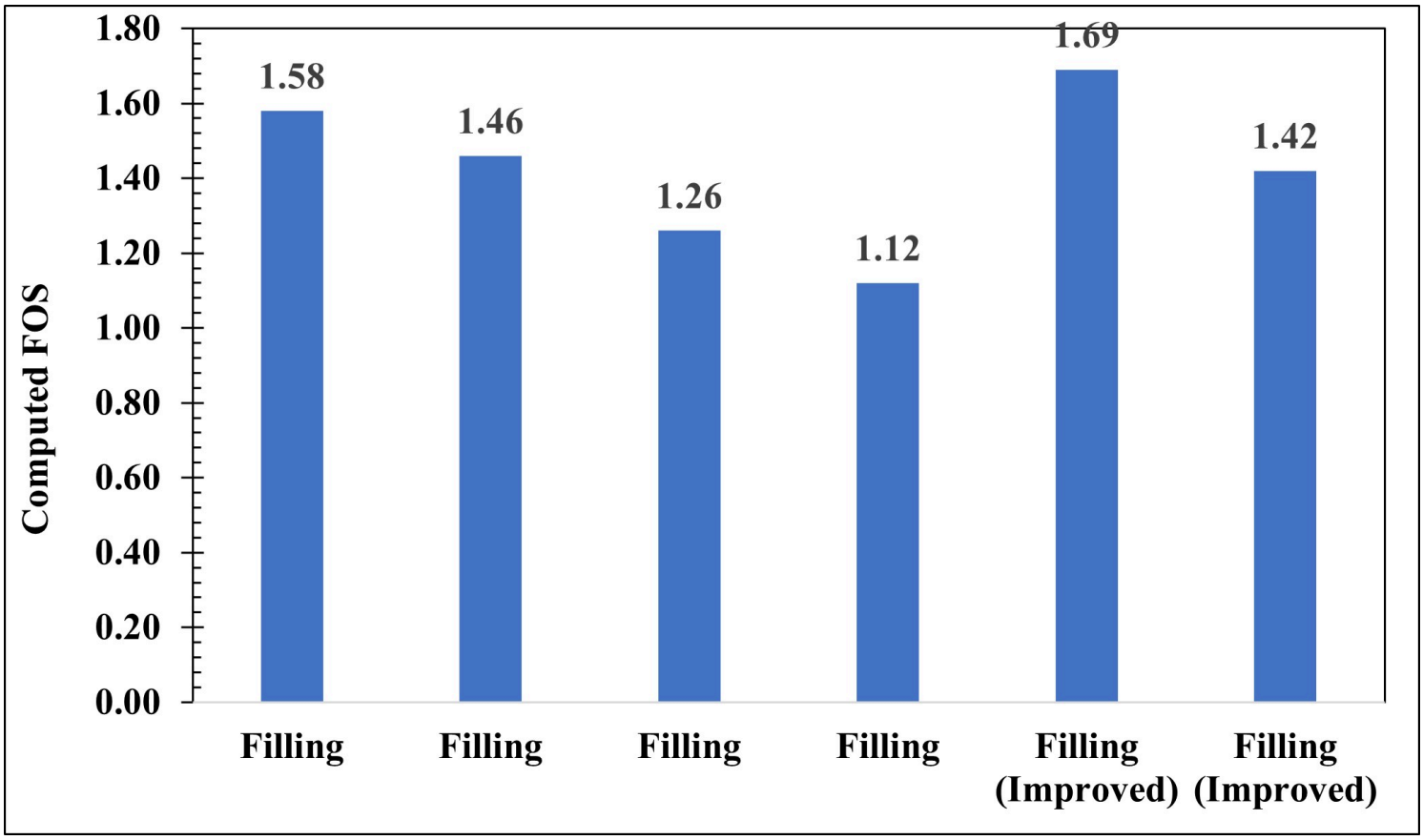


Figure 2

Improvement in slope stability achieved through rockfill replacement and staged construction in water-logged filling locations

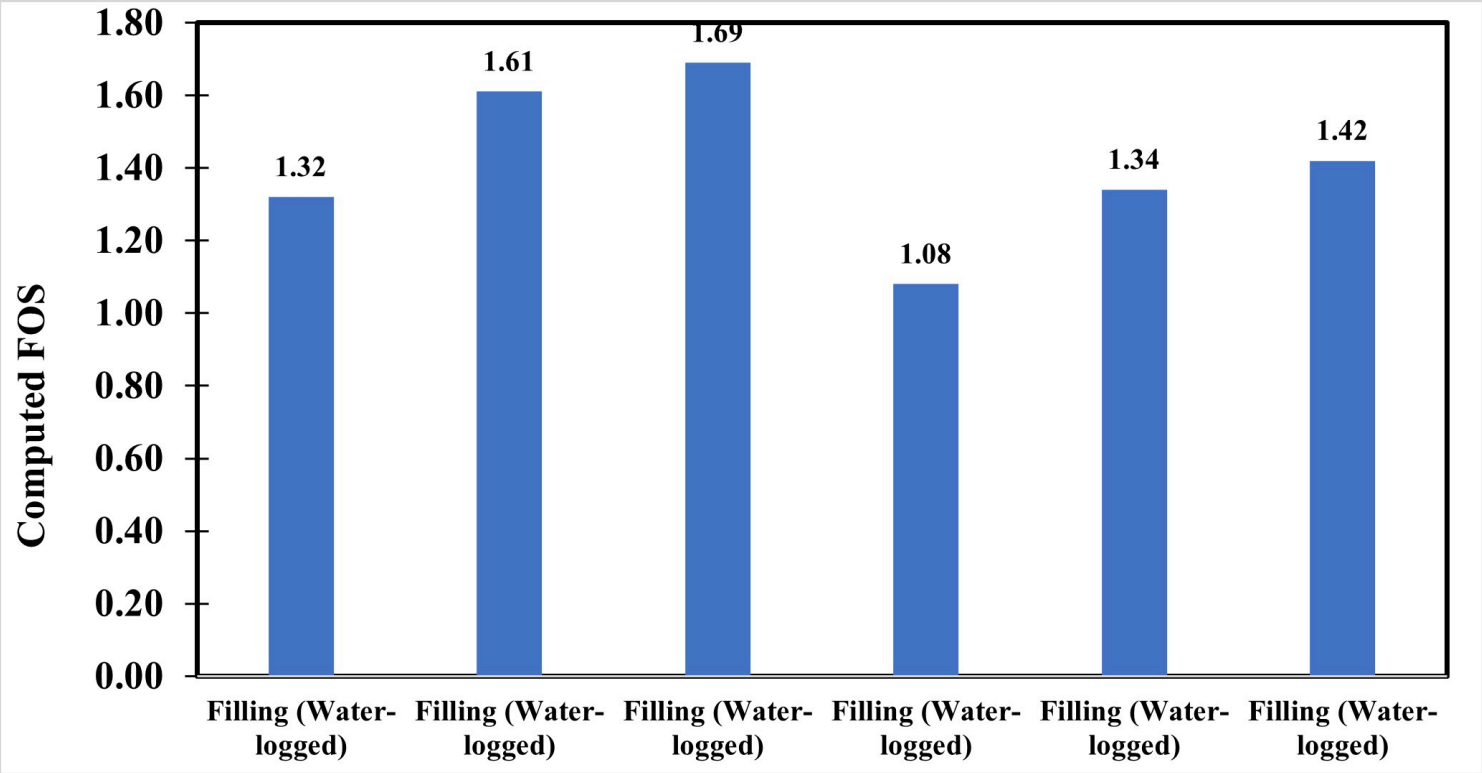


Figure 3

Impact of groundwater conditions and soil improvement measures on the stability of cutting and filling slopes

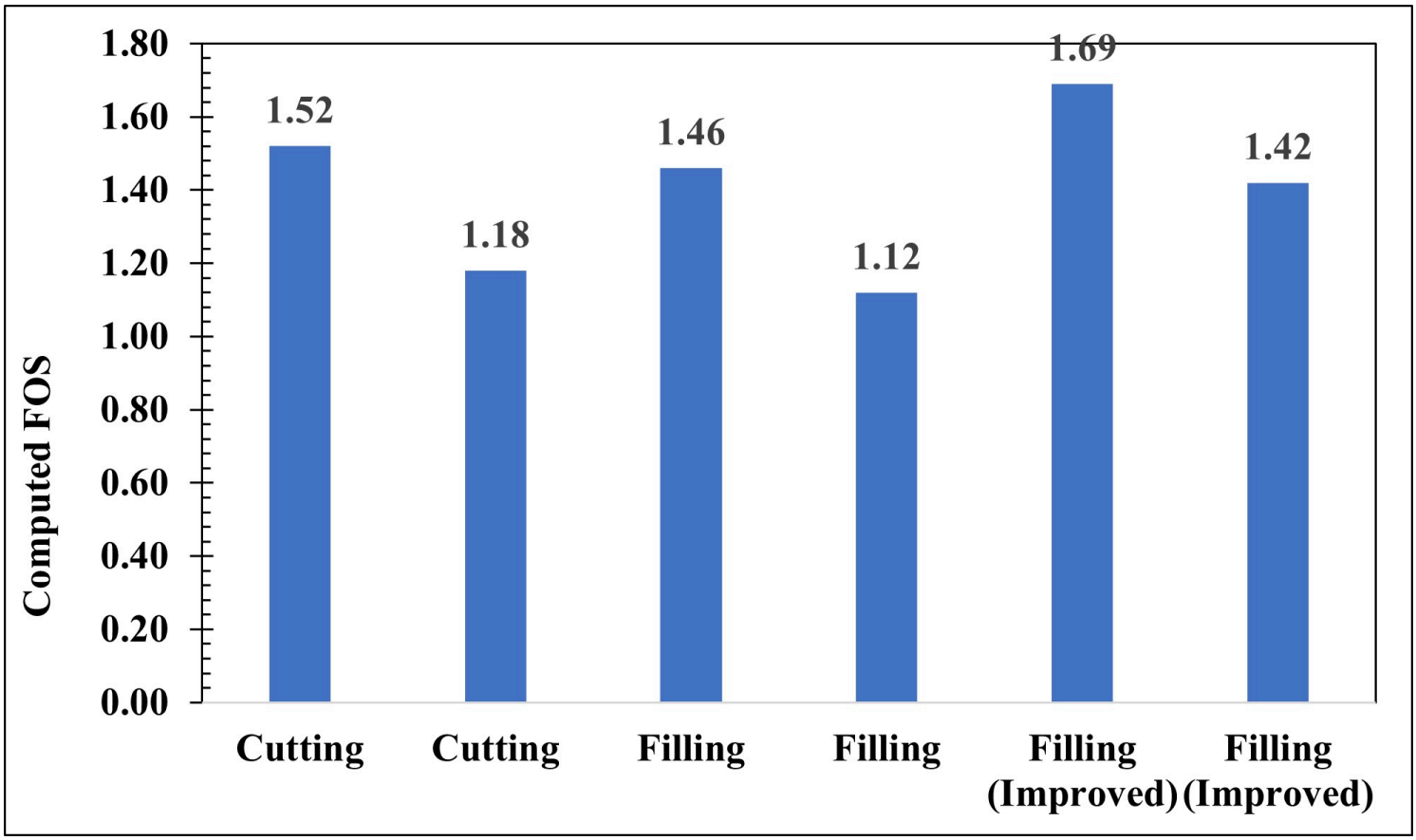


Figure 4

Traffic Surcharge and Shear Strength Parameters on Factor of Safety

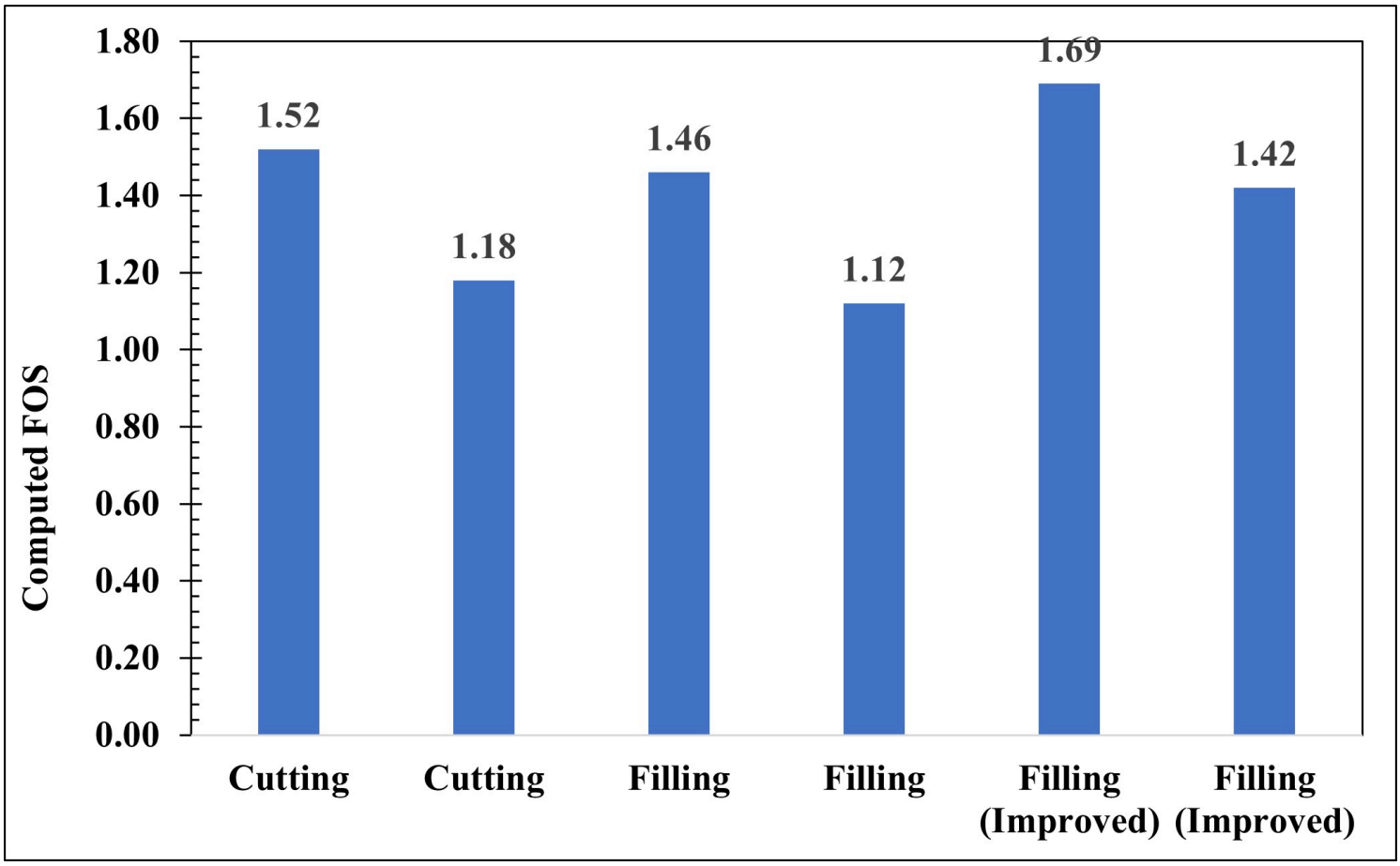


Figure 5

Comparative Factor of Safety for Cutting and Filling Slopes