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Conceptual Effects of Vegetation on the Stability of a Soil Dyke: A Case Study with Emphasis on Vetiver Grass in India

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Abstract. This study investigates the use of Vetiver grass for stabilizing soil dykes, combining field experiments, laboratory analyses, and numerical modelling to assess its efficacy. Key findings demonstrate the significant impact of Vetiver grass on improving soil strength and stability, particularly under varying environmental conditions. Results suggest that this method offers a sustainable and cost-effective alternative to conventional stabilization techniques, with potential applications in flood-prone areas. Limitations and future research directions are also discussed.

1. Introduction

Soil dykes are critical infrastructure elements in flood management and land reclamation projects worldwide. By serving as barriers against water intrusion, they protect agricultural lands, populated areas, and ecological habitats from the destructive forces of water. The stability of these structures is paramount to their effectiveness and longevity. However, soil dykes are susceptible to various forms of erosion and structural failure, often exacerbated by environmental factors and human activities. Among the myriad factors influencing dyke stability, vegetation plays a complex role. While traditionally viewed as a threat due to root penetration and moisture dynamics, recent studies suggest that vegetation can also reinforce dyke structures, enhance soil cohesion, and reduce erosion. The vegetation influences slope stability in two ways: through hydrological effects and mechanical effects [1]. Hydrological effects involve removing soil water by evapo-transpiration through vegetation, which increases soil suction or a reduction in pore-water pressure, increasing the soil shear strength.

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The shear strength of the soil is also increased through the mechanical effects of the plant root matrix system. The density of the roots within the soil mass and the root tensile strength contribute to the ability of the soils to resist shear stress. The effects of soil suction and root reinforcement have been quantified as an increase in apparent soil cohesion.

1.1 Role of Vegetation in Soil Stabilization

Vegetation has long been recognized for its significant role in soil stabilization and erosion control. According to Ziemer [2], plant roots can enhance soil shear strength through root reinforcement, where roots interlock with soil particles, creating a more cohesive and stable matrix.

Furthermore, Wu et al. [3] introduced a quantitative model for evaluating the reinforcement effects of roots on soil shear strength, underscoring the potential for vegetation to contribute to slope and dyke stability. Different plant species and their root systems can have varying effects on soil aggregate stability, with some increasing stability and others potentially decreasing it [4-5]. The spatial layout of vegetation on slopes can also impact stability, with closer root systems generally providing more excellent stability [6]. Fibrous roots such as Vetiver's roots can improve stability with the advantages of erosion control.

The application of vegetation in enhancing dyke stability has explicitly garnered attention in recent years [7-8]. Stokes et al. [9] discussed the dual role of vegetation in providing surface protection against erosion and contributing to the mechanical stability of earthen structures through root-soil interactions [9]. However, the effectiveness of vegetation cover in reinforcing dykes can vary significantly depending on plant species, root architecture, and soil conditions, as highlighted by in their work on biotechnical and soil bioengineering slope stabilization [10].

1.2 Vegetation's Lifecycle Impact on Dyke Stability

The lifecycle of vegetation, notably the transition from living to deceased plant matter, presents unique challenges and opportunities for soil dyke stability. Baets et al. [11] explored the protective effects of dead roots on soil erosion, suggesting that the decaying root systems could still contribute to soil cohesion and reduce runoff-induced erosion for a period of decomposition. This aspect of vegetation's lifecycle impact on soil and structural stability, especially in the context of dykes, has not been thoroughly examined and represents a gap in the current literature.

1.3 Importance of Vetiver Grass for Dyke Stability

Chrysopogon zizanioides, commonly known as Vetiver, is a renowned phyto-stabilizer, and the World Bank introduced it to mitigate soil erosion problems worldwide. It has gained prominence as a widely adopted phytostabilizer and soil erosion control method across the globe. This grass boasts a distinctive feature a lengthy fibrous root system that can sometimes extend up to 3.5 meters. These roots possess noteworthy morphological attributes such as bulk shear and tensile strengths. Grimshaw [12] states that Vetiver is a solution for many geotechnical problems in America, highlighting the reinforcement effect offered by tree roots and other vegetation, elucidating their role in conferring soil stability through attributes like tensile resistance, frictional properties, and adhesion. This grass has been found to significantly enhance soil shear strength, leading to increased slope stability [13] in several research. However, its impact on slope stability can vary depending on factors such as soil type and slope gradient [14]. In field studies, Vetiver has been shown to reduce soil erosion and improve slope stability, particularly in sandy soils [15]. Vetiver also has excellent tolerance to nutrient deficiency stresses, heavy metal toxicity incidences of fire outbreaks, etc. It makes Vetiver grass one of the best candidates for stabilisation of dykes of toxic wastewater reservoirs.

Unlike traditional stabilization techniques, such as chemical or mechanical methods, Vetiver grass offers a sustainable and eco-friendly alternative. This study uniquely integrates field tests, laboratory experiments, and numerical simulations to evaluate the performance of Vetiver grass in stabilizing soil dykes. The comprehensive approach ensures a holistic understanding of its effectiveness, setting it apart from prior research that predominantly focused on isolated methodologies. The objectives of this research are threefold: first, to assess the stability of a soil dyke in its initial, vegetation-free state, offering a baseline for comparison; second, to analyze the effect of living vegetation on dyke stability, reflecting the most common scenario over a dyke's operational lifespan; and third, to evaluate the stability implications of deceased vegetation, a condition that represents the lifecycle's end-stage for perennial plant species. This comprehensive approach allows for a nuanced understanding of how vegetation, both in life and death, impacts the structural integrity of soil dykes. This study aims to bridge this gap by examining the stability of soil dykes under varying vegetation conditions.

2. Methodology

2.1 Study Site

This study is conducted on the dykes of wastewater reservoirs of a thermal power plant situated within 1 Km from Mecheda, 55 km approximately from Kolkata by Southeastern Rail or by NH-6. This thermal power plant is a coal-fired thermal power Plant consisting of 6 Units of 210 MW each (Fig. 1). The fly ash generated in the plant is discharged in wastewater reservoirs.

Fig. 1. Location Map of the Wastewater Reservoir at the Thermal Power Plant

2.2 Laboratory Testing (Direct Shear Test)

2.2.1 Preparation of Sample with Vetiver Plantation

Soil samples from the dykes of wastewater reservoirs of the study site are collected by random sampling and screened to pass through a standard sieve of No. 4 mess (4.75 mm) to avoid larger stones. These soils are mechanically mixed with compost of 50% by weight, and two slips of Vetiver are planted in dismountable sample pots (Fig. 2a) identical to the shear box of Direct Shear Apparatus for about eight months till the growth of Vetiver is almost negligible. The shoot part of these Vetiver is then harvested, and plates of shear pots are cut open to have a cubical rooted soil mass (Fig. 2b) for direct shear test. Fig. 2. Shows the Various Processes of the Direct Shear Test

2.2.2 Direct Shear Tests

A digital direct shear apparatus (Make – HEICO; Model – HS 24.622) with a box size of 100 mm × 100 mm × 100 mm is selected for the test. Fig. 3 shows the Shear stress versus shear displacement relationships for dyke material It has a maximum shear loading of 50kN and an average loading capacity of 5kg/cm^2. The shearing rate is applied at 1.25 mm/min, and the data is logged at an interval of 2s in the computer, automatically generating load versus displacement curves (Fig. 3a and Fig. 3b). Direct shear testing is conducted at various normal loads (σ =1 kPa, 2 kPa, 3 kPa etc.) to determine the cohesion (C) and angle of internal friction (ϕ) by drawing the failure envelope directly from the maximum shear stresses (τ_p) against normal loads (σ) where the intercept on shear stress axis gives values of cohesion (Figure 3c and d) and the internal friction angle (ϕ) is the tangent inverse of the slope of failure envelope($\frac{\Delta\tau}{\Delta\sigma}$) as per the following expression:

$$\text{Angle of internal friction, } \phi^0 = \{\tan^{-1}(\frac{\Delta\tau}{\Delta\sigma})\} \times \frac{180}{\pi}$$

These direct shear tests are performed to simulate the conditions of the soil of dyke under the following scenarios outlined in the study:

- *pre-plantation:* The baseline condition without vegetation (on bare soil before Vetiver plantation).
- *with Vetiver roots*: To assess the impact of living vegetation on soil stability (on rooted soil sample).
- *without Vetiver roots:* To understand the effects after the vegetation has died (on recovered soil separated from sheared roots after previous direct shear tests)

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Fig. 2. Various Processes of the Direct Shear Test: (a & b) Sample Preparation with Roots, (c) Placement of Samples in the Shear Machine, (d) Sheared Sample, and (e) Recovery of Soil and Sheared Roots.

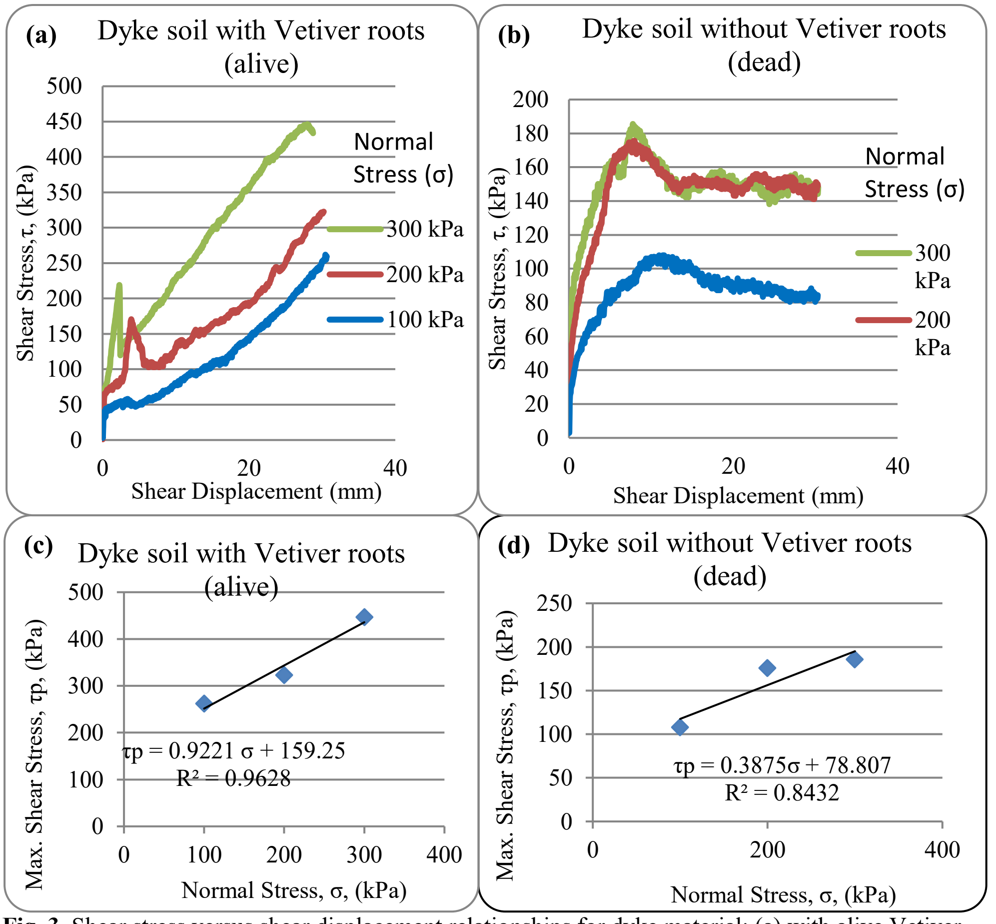

Fig. 3. Shear stress versus shear displacement relationships for dyke material: (a) with alive Vetiver and (b) with dead Vetiver; failure envelopes for the dyke material: (c) with alive Vetiver and (d) with dead Vetiver.

2.3 Numerical Analysis

2.3.1 Factor of Safety Analysis Software

The safety factor for various samples is estimated using *SLIDE* Software by *Rocscience Inc.* (Canada) on a test slope with layers with the same values of C and ϕ obtained from the Direct Shear Tests mentioned above. Notably, this FOS analysis is a numerical approach using a method called Bishop Simplified analysis. It is assumed that the strength indices (C and ϕ) obtained from the direct shear tests would be constant up to a root depth of 1 m, which is not the actual scenario.

2.3.2 Dyke Geometry and Loading Conditions

The dykes in the study sites are trapezoidal in cross-section with top floor width of 4 m with the extension of the rectangular back floor. It is laid over the in-situ ground for a

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length of 35.5m and a height of 10m. The front and back slope has a slope angle 34^0 to the horizontal line. It has a small benching of 1.5mwide at 5m height from the ground in front slope (free face). The front slope is assumed to be water-logged up to 9m from the ground. The Vetiver is assumed to grow and form a rooted soil material boundary of 1m depth in all the peripheral boundaries of dyke (Fig. 4). The material properties used in the analysis are shown in Table 1. The case of pre-plantation is one without any root boundary. The material 'with roots' has the values of C and ϕ of rooted samples prepared from the Vetiver plantation.

2.3.3 Justifying Numerical Analysis Assumption

Key assumptions in the numerical analysis include:

- Soil properties were derived from standard field tests and validated against laboratory results.
- The strength indices for soil with Vetiver roots were assumed based on empirical studies, adjusted for local environmental conditions.
- Boundary conditions mimic real-world scenarios, including seasonal variations in moisture and temperature.

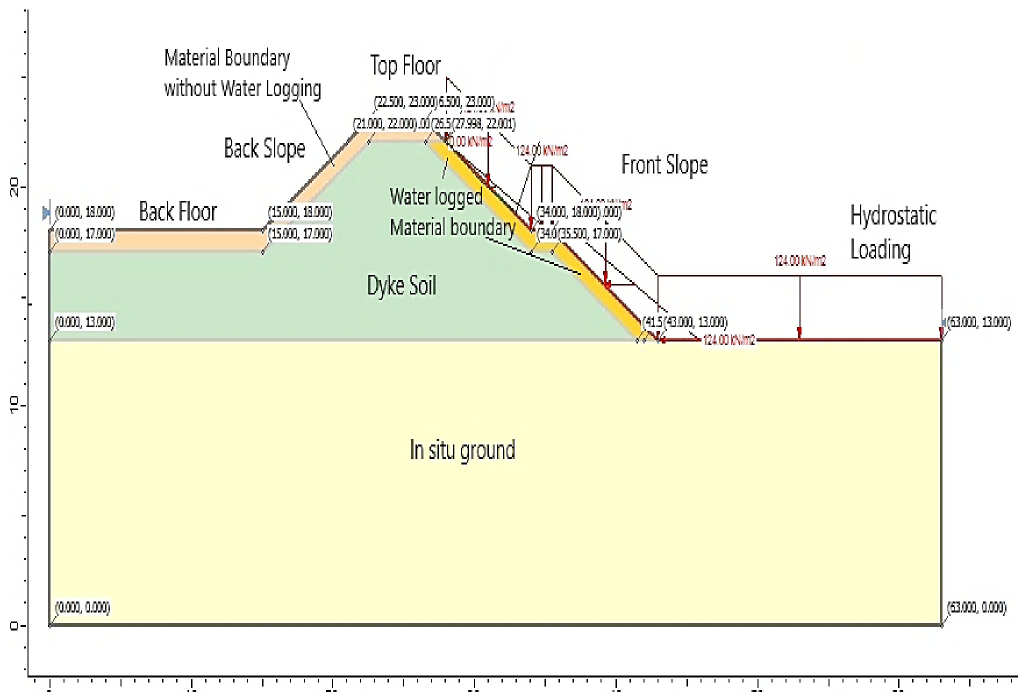


Fig. 4. Dyke geometry with coordinates and locations of Vetiver plantation sites

Table 1. Material properties of dyke constituents used in the numerical analysis

Material Name	Colour	Unit Weight (kN/m^3)	Strength Type	Cohesion (kN/m^2)	Phi (^{0})	Ru
Soil		17.5	Mohr-Coulomb	20	22	0
Dyke Material		14.5		34.34	22.87	0
Dyke material with Vetiver roots (alive)		14.5		159.25	43.91	0
Dyke Material without Vetiver roots (dead)		14.5		78.81	21.18	0

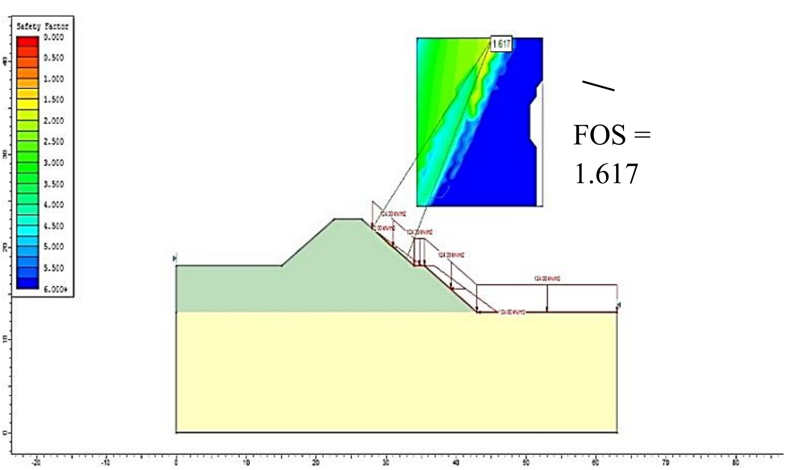
Material 'without roots' has the values of C and ϕ of recovered soil, assuming that these soils will have residues of dead roots in them after root recovery, mimicking the absence of roots after decomposition. It is also assumed that the condition of dead roots (without roots) will be found in the water-logged portion of the front slope. A constant hydrostatic pressure of 124 kN/m^2 is distributed on the ground, and triangular hydrostatic loading of 124 kN/m^2 at the base of the front slope and zero at a vertical height of 9m is applied to simulate the hydrostatic pressure of water found on the dyke of the wastewater reservoir.

3. Results and discussions

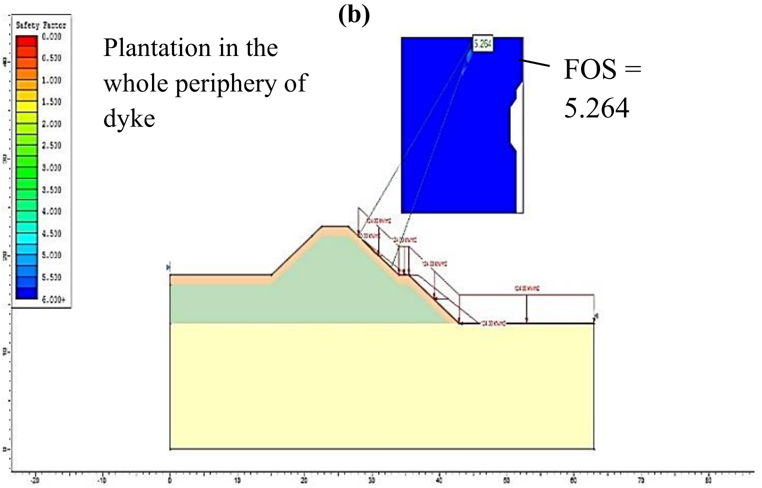
The shear stress versus shear displacement curves demonstrates a gradual increase after an initial spike (root failure), indicating that Vetiver roots can withstand shear stress post-breakage in the case of living Vetiver on dyke. This behaviour aligns with the strain-hardening characteristic of root systems (Fig. 3). Conversely, in the case of Vetiver death, the curves slope downward after reaching a plateau, demonstrating strain-softening behaviour, similar to soil without vegetation. Despite the roots' death, a significant amount of cohesion remains, likely due to the presence of broken rootlets, which may also promote microbial growth, further stabilising the soil. However, no notable impact is observed on the internal friction angle of the dyke material after Vetiver dies.

The analysis of the factor of safety of dyke for various conditions of Vetiver plantation is shown in Fig. (5).

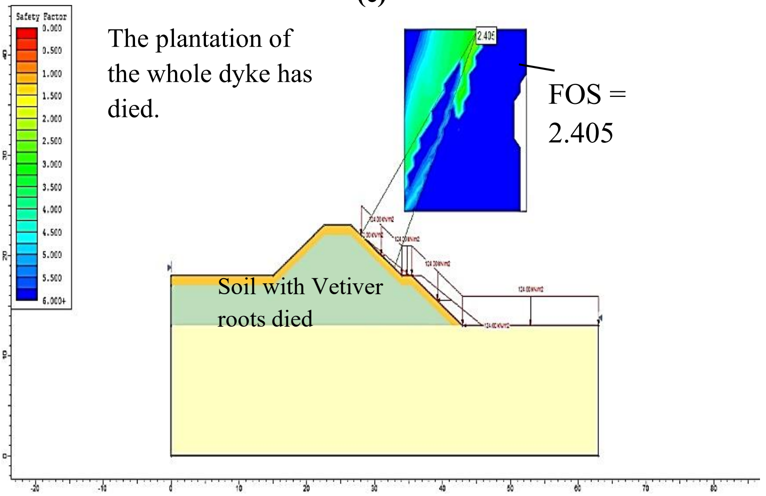
(a)



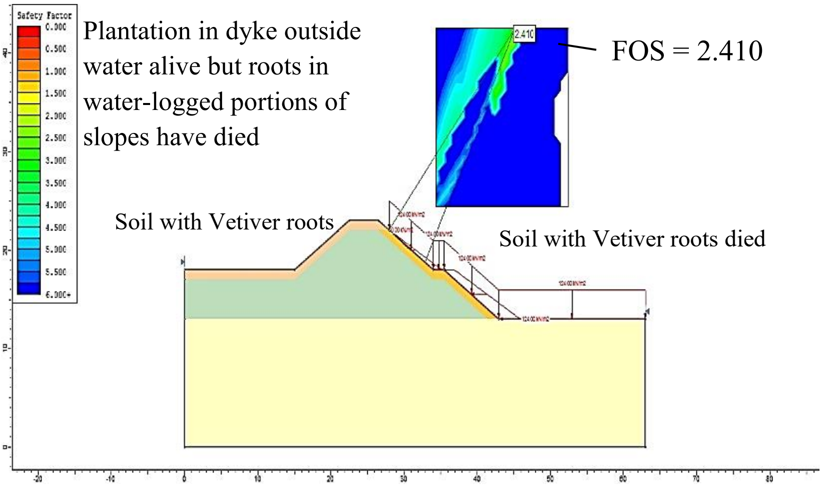
(b)


Safety Factor
Plantation in the whole periphery of dyke
FOS = 5.264
5.264

(c)


Safety Factor
The plantation of the whole dyke has died.
FOS = 2.405
2.405
Soil with Vetiver roots died

(d)


Safety Factor
Plantation in dyke outside water alive but roots in water-logged portions of slopes have died
FOS = 2.410
2.410
Soil with Vetiver roots
Soil with Vetiver roots died

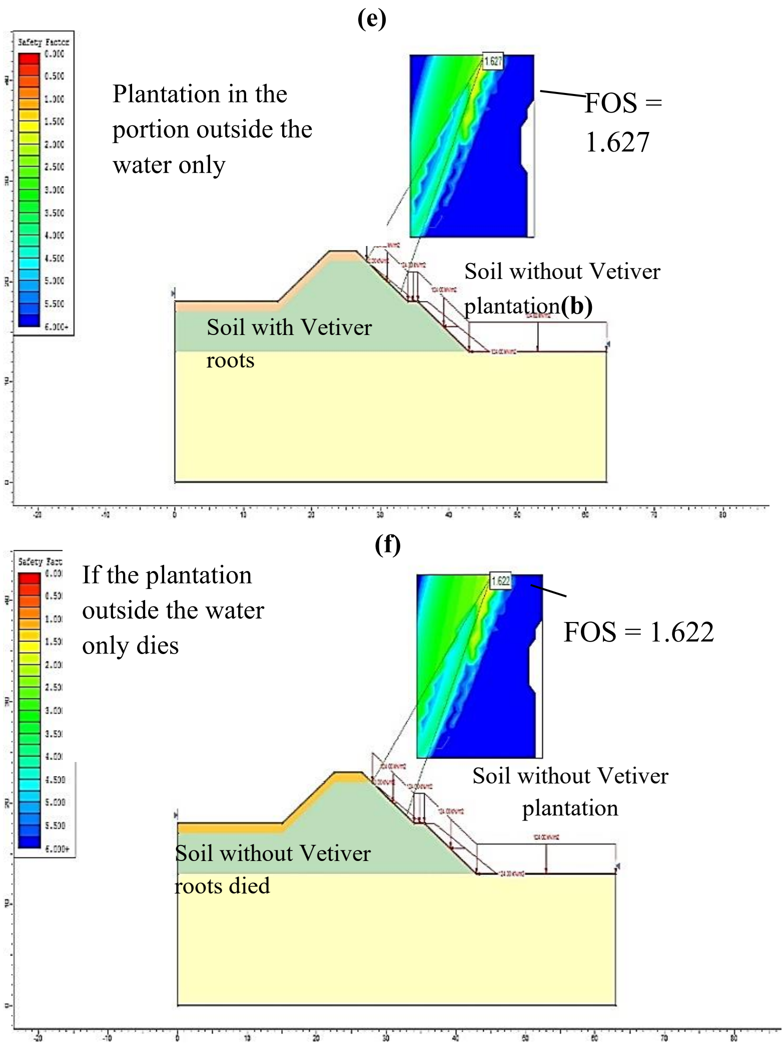


Fig. 5. Factor of safety analysis for different scenarios of Vetiver plantation on the dyke

From the results of the factor of safety (FOS) analysis, it is found that the dyke with its geometry is already stable without plantation (FOS>1). However, the plantation of the Vetiver has increased the FOS from 1.617, which is the case of pre-plantation, to a maximum of 5.264 (225.54% increase) when the whole periphery of dyke is vegetated with Vetiver roots. If the whole peripheral vegetation dies, leaving the dead and decomposed roots, the residual FOS remains at 2.405 (48.73% more). However, if vegetation on only the water-logged portion dies and Vetiver outside water sustains, the FOS would be 2.410, which is 49.04% more than that of pre-plantation. If the only portion outside the water is planted with Vetiver, leaving the portion of the front slope to be waterlogged (barren), the FOS would be 1.627 (0.62% more) with Vetiver roots, and when it dies, the same would be 1.622 (0.31% more). It shows that FOS improves with plantation irrespective of portions of dyke are vegetated and the condition of Vetiver. The vegetation of the front slope prone to dynamic loading and tending to fail brings phenomenal improvement in safety as found numerically.

4. Conclusions

This research highlights the critical role of Vetiver vegetation in improving the stability and safety of dykes. The findings suggest that strategic plantation of Vetiver not only significantly boosts the Factor of Safety under various conditions but also offers a resilient and sustainable approach to managing the integrity of dyke structures against dynamic loads and potential sliding. These insights underscore the importance of incorporating vegetation, especially Vetiver, in the design and maintenance of dykes as a cost-effective, environmentally friendly, and efficient method of enhancing structural stability and safety. Specifically, the introduction of Vetiver on the entire periphery of the dyke increases the FOS. This improvement is substantial and persists, to a considerable extent, even when the vegetation dies. Furthermore, the study reveals that selective plantation in areas outside water-logged portions yield a marginal increase in FOS.

The study is limited by its reliance on specific soil types and controlled laboratory conditions. Real-world variability, such as extreme weather events and soil heterogeneity, could impact results. Additionally, long-term performance under sustained loading remains untested. Future research should address these aspects to generalize findings more effectively.

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