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Slope Stability Analysis of Highway Embankments Using Strength Reduction Method in PLAXIS 3D

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Abstract: Slope stability analysis is vital in geotechnical and highway engineering due to its direct implications on infrastructure safety and serviceability. This study employs the Strength Reduction Method (SRM) in PLAXIS 3D, a finite element-based software, to assess the stability of highway embankments under various slope geometries, embankment heights, and groundwater table (GWT) positions. A total of 72 cases were analysed, involving six slope ratios (1.25H:1V to 3.5H:1V), six embankment heights (1 m to 10 m), and two groundwater conditions (−4 m and 0 m). Results show that the Factor of Safety (FOS) decreases with increasing slope steepness and embankment height, while gentler slopes consistently exhibit higher FOS values. Rising the GWT to ground level reduced FOS values by up to 35%, highlighting the destabilizing role of elevated pore-water pressures. Comparative analysis revealed that gentler slopes improved FOS by up to 50% compared to steep slopes at higher embankments. The findings underscore the importance of adopting flatter slopes and effective drainage strategies in highway embankment design to ensure long-term stability.

Keywords: Slope Stability; Factor of Safety; Embankment; PLAXIS 3D; Strength Reduction Method;

I. INTRODUCTION

Slope stability is a critical concern in civil engineering, especially for highways, railways, and embankments, where slope failures can cause severe economic and social losses(1,2). Traditional slope stability methods such as the Limit Equilibrium Method (LEM) are widely used but limited by their reliance on pre-defined slip surfaces. Finite Element Method (FEM) approaches, particularly the Strength Reduction Method (SRM), offer improved accuracy by simulating soil stress-strain behavior and failure mechanisms(3,4). Previous studies (5–9)have highlighted the influence of slope geometry, soil parameters, and groundwater conditions on the factor of safety (FOS). However, most investigations focus on natural slopes or simplified 2D analyses, leaving a gap in understanding the 3D stability of engineered embankments.

This study addresses these gaps by using PLAXIS 3D to assess the effect of slope angle, embankment height, and groundwater conditions on the stability of highway embankments. The outcomes contribute to practical guidelines for designing safer and more resilient highway slopes.

II. MATERIALS AND METHODS

The study area lies along the Ganga Expressway corridor in Uttar Pradesh, India. Soil samples from five representative locations were tested to determine geotechnical properties. The embankments were modelled with six slope ratios (1.25H:1V, 1.5H:1V, 2.0H:1V, 2.5H:1V, 3.0H:1V, 3.5H:1V) and six heights (1 m, 2 m, 4 m, 6 m, 8 m, 10 m). Two groundwater scenarios were analyzed: GWT at −4 m and GWT at ground level (0 m). Numerical modelling was performed in PLAXIS 3D (version 2023.2) using the Mohr–Coulomb constitutive model under drained conditions(10). The Strength Reduction Method (SRM) was applied to compute FOS by progressively reducing the shear strength parameters until failure occurred. A summary of the properties of soil samples is presented in Table 1.

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Flowchart of methodology adopted for slope stability analysis is given in Figure 1.

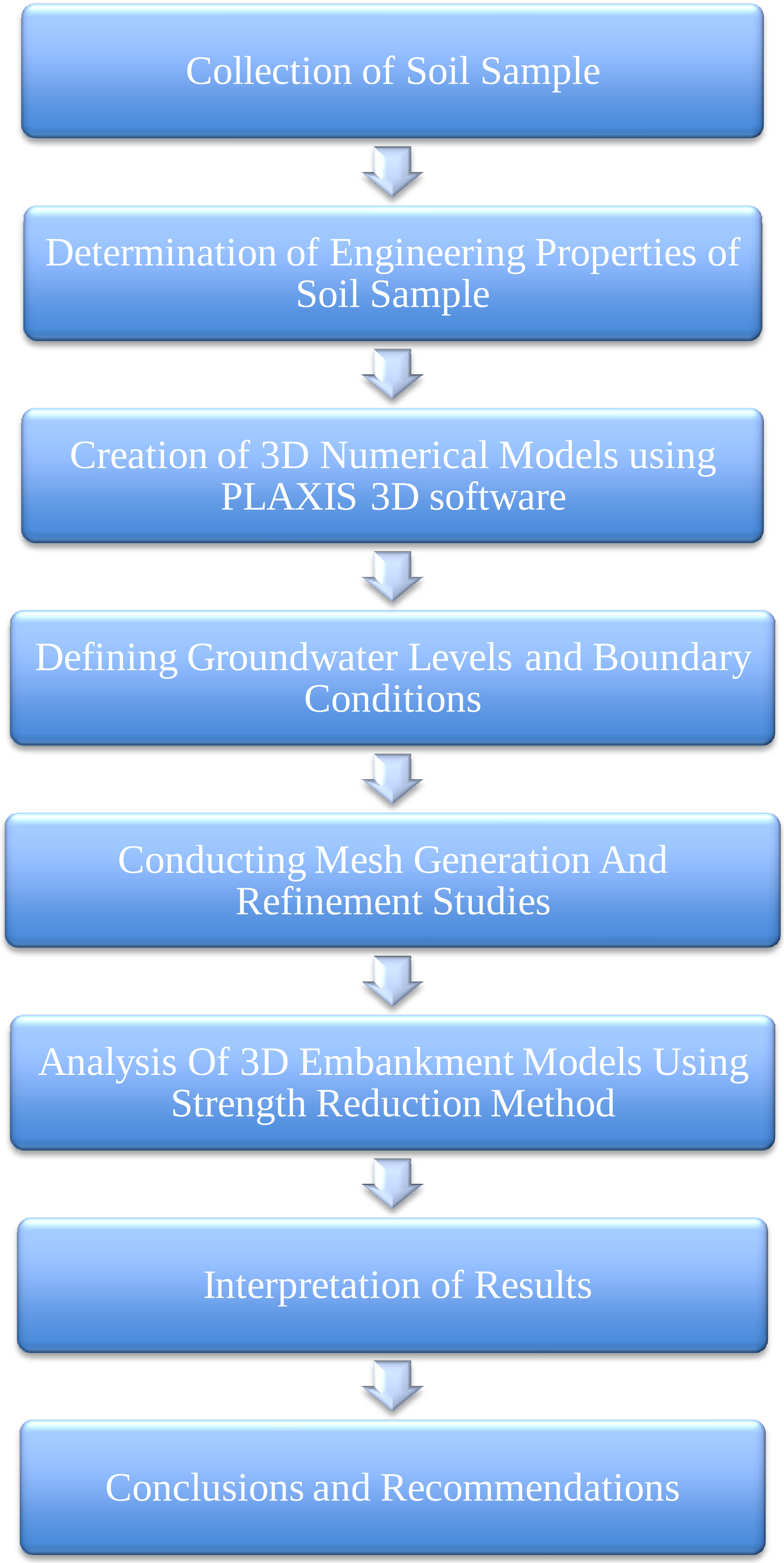

Figure 1Flowchart of Methodology for 3D Slope Stability Analysis

Table 1Soil Properties from Laboratory Tests and Parameters Used in PLAXIS 3D

S. No	Property		Embankment Fill (CL)	Subsoil Layer 1 (MI)	Subsoil Layer 2 (CL)
1	Gravel (%)		11.5	7.0	8.0
2	Sand (%)		40	38	39
3	Silt & Clay (%)		48.5	55	53
4	Liquid Limit (%)		34	35.1	32
5	Plastic Limit (%)		22.9	20.2	21.5
6	Plasticity Index (%)		11.1	14.9	10.5
7	Specific Gravity (G_s)		2.65	2.45	2.50
8	Maximum Dry Density (g/cc)		1.98	1.80	1.76
9	Optimum Moisture Content (%)		11.5	Natural	Natural
10	Void Ratio	e	0.31	0.41	0.35
11	Dry unit weight (kN/m³)	γ_{dry}	18.0	17.0	18.2
12	Unsaturated unit weight (kN/m³)	γ_{unsat}	19.1	18.0	19.3
13	Saturated unit weight (kN/m³)	γ_{sat}	20.2	19.1	20.4
14	Cohesion (kPa)	c	25	18	30
15	Friction Angle	ϕ, °	21	17	23
16	Dilatancy Angle	ψ, °	0	0	0
17	Young's Modulus (kPa)	E	12000	9000	15000
18	Poisson's Ratio	ν	0.30	0.30	0.30

III. GEOMETRY OF THE SLOPE

The Ganga Expressway is designed as a 6-lane divided carriageway, comprising two 3-lane roadways in each direction, separated by a median. For this numerical study, only one side of the embankment (i.e., a single 3-lane carriageway) was modelled in PLAXIS 3D. This simplification is sufficient for evaluating slope stability, as both sides of the embankment are typically constructed symmetrically and analysed independently unless site-specific asymmetry or median loading exists.

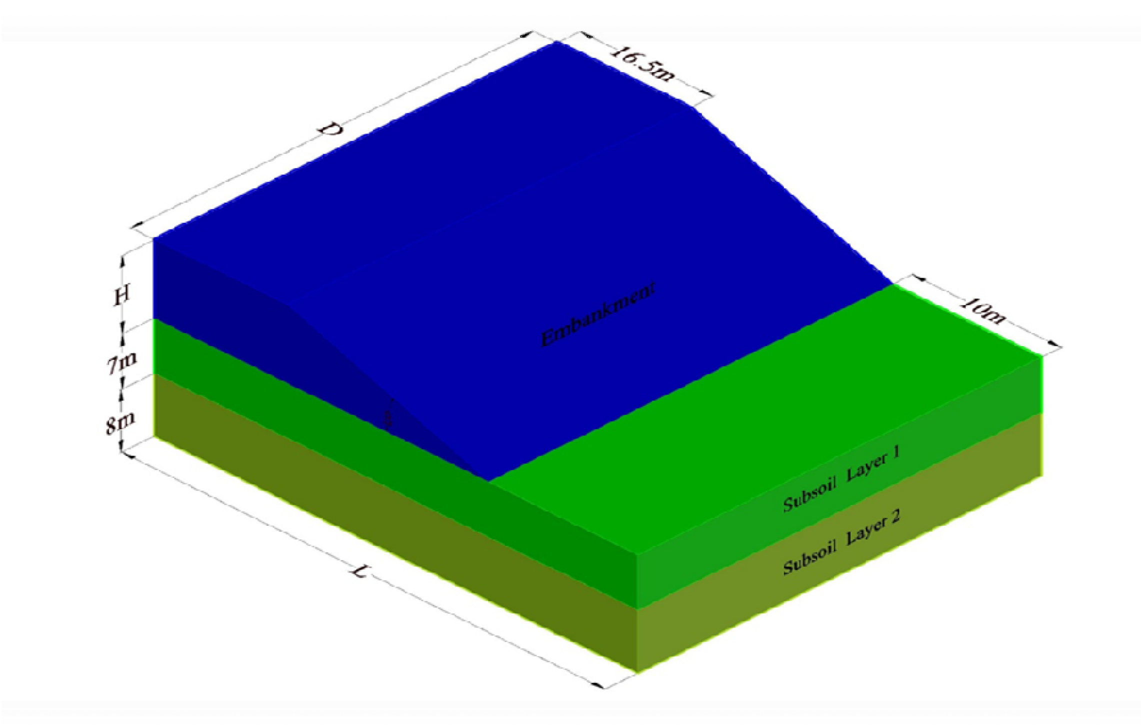

Figure 2Geometry of the Slope along with different soil layer

The geometric model developed in PLAXIS 3D represents the embankment resting over two distinct subsoil layers, with dimensions carefully chosen to replicate realistic field conditions while ensuring numerical stability. The crest width of the embankment is fixed at 16.5 m, corresponding to the carriageway and shoulder widths prescribed in highway design standards. The third dimension, denoted as D, is defined as a function of the slope height (H) and the adopted slope ratio (H:V), such that it accommodates the full lateral spread of the embankment including the side slopes. In 3 D slope stability analysis, using sufficient length in the third dimension is crucial. Studies have shown that the third/longitudinal dimension of the slope should not be less than 4 H(11,12).In this study the third dimension (D) is taken as 5 times the height of embankment (H).

Parametric Framework for Numerical Stability Analysis

To comprehensively evaluate the stability of highway embankments under varying geometric and groundwater conditions, a total of 72 simulations were performed in PLAXIS 3D. These cases were developed by combining six different slope ratios (1.25H: 1V, 1.50H: 1V, 2.0H: 1V, 2.5H: 1V, 3.0H: 1V, and 3.5H: 1V) with six embankment heights (1 m, 2 m, 4 m, 6 m, 8 m, and 10 m) under two distinct groundwater table (GWT) scenarios: GWT at –4 m and GWT at 0 m relative to the ground surface. The resulting simulation matrix is presented in Table 6, serving as the basis for the parametric study and subsequent factor of safety (FOS) evaluation

Table 2Matrix of slope geometry and GWT conditions for stability analysis.

Series	Constant Parameters	Variable Parameters	GWT Level
1	Slope (1.25H:1V)	H = 1, 2, 4, 6, 8, 10 m	-4 m
2	Slope (1.50H:1V)	H = 1, 2, 4, 6, 8, 10 m	-4 m
3	Slope (2.0H:1V)	H = 1, 2, 4, 6, 8, 10 m	-4 m
4	Slope (2.5H:1V)	H = 1, 2, 4, 6, 8, 10 m	-4 m
5	Slope (3.0H:1V)	H = 1, 2, 4, 6, 8, 10 m	-4 m
6	Slope (3.5H:1V)	H = 1, 2, 4, 6, 8, 10 m	-4 m
7	Slope (1.25H:1V)	H = 1, 2, 4, 6, 8, 10 m	0 m
8	Slope (1.50H:1V)	H = 1, 2, 4, 6, 8, 10 m	0 m
9	Slope (2.0H:1V)	H = 1, 2, 4, 6, 8, 10 m	0 m
10	Slope (2.5H:1V)	H = 1, 2, 4, 6, 8, 10 m	0 m
11	Slope (3.0H:1V)	H = 1, 2, 4, 6, 8, 10 m	0 m
12	Slope (3.5H:1V)	H = 1, 2, 4, 6, 8, 10 m	0 m

IV. RESULTS

Results are presented in four categories:

A. Effect of slope angle and height when GWT = −4 m

At −4 m GWT, FOS values decreased sharply with increasing embankment height. For example, at 1.25H:1V, FOS reduced from 7.229 (1 m) to 1.504 (10 m). Gentler slopes consistently showed higher FOS values; at 10 m, FOS ranged from 1.504 (steepest) to 2.324 (gentlest).

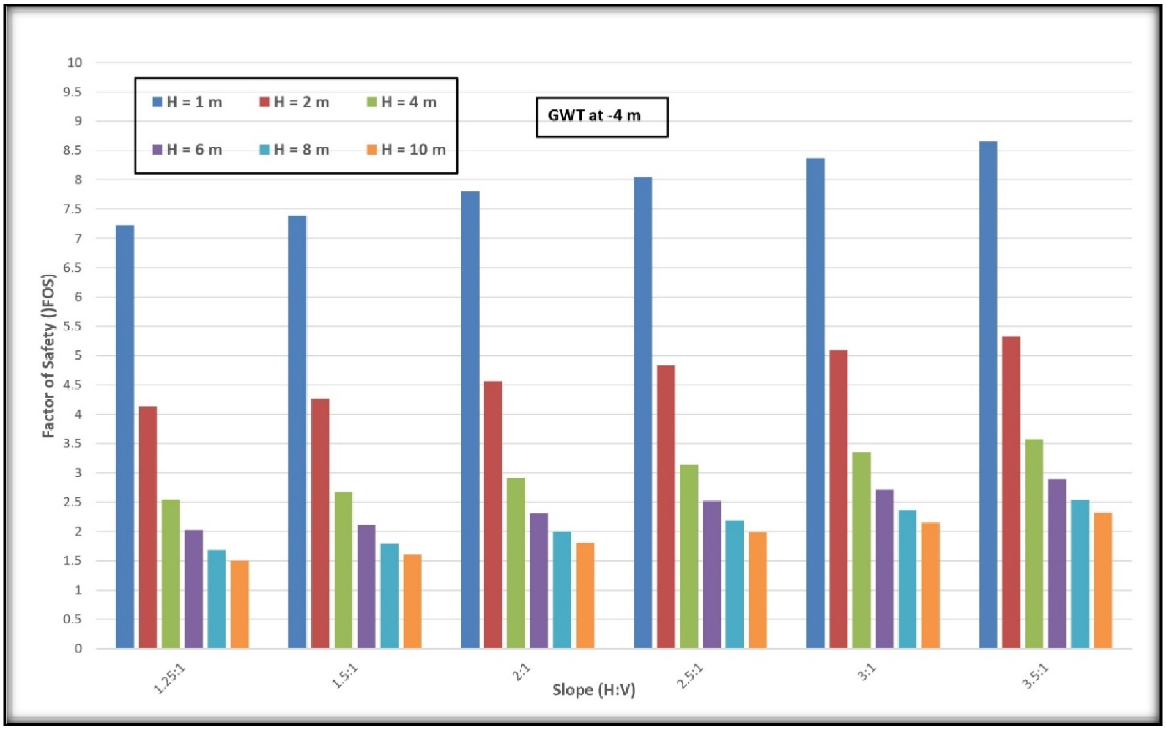

Figure 3Graphical Representation of variation of FOS with Slope Angle and Height (GWT = -4 m)

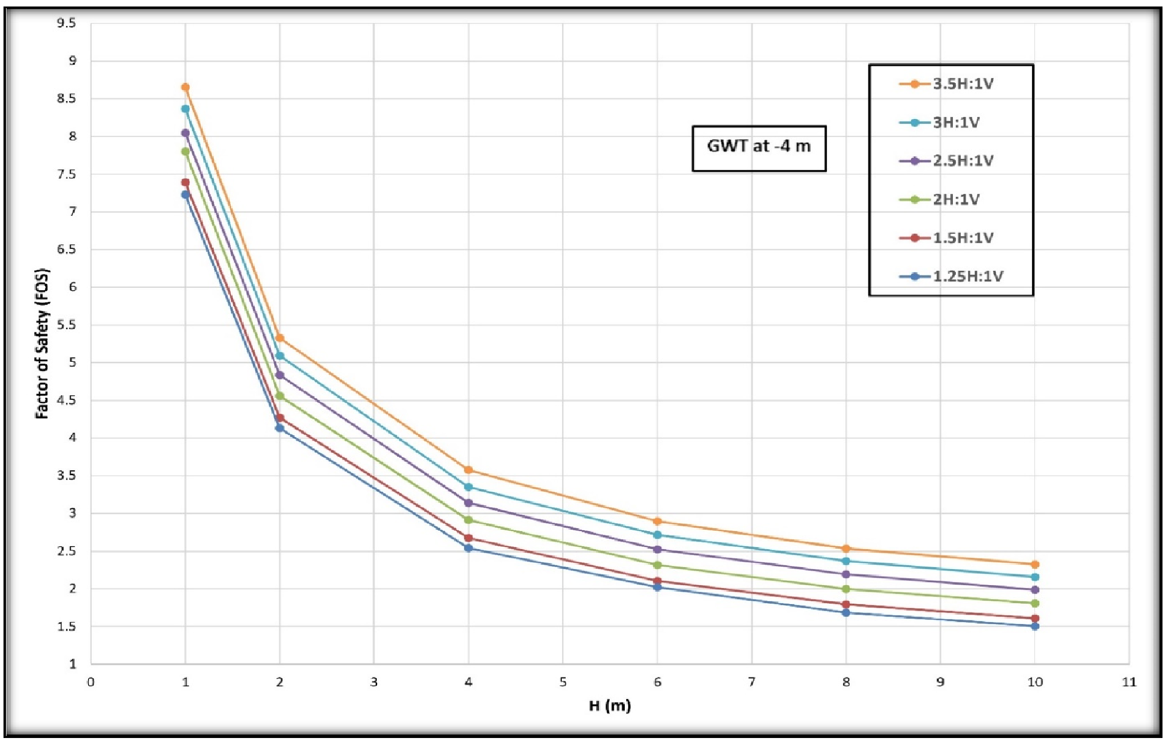

Figure 4 Variation of FOS of slope with various slope angles and heights at (GWT -4)

B. Effect of slope angle and height when GWT = 0 m

At 0 m GWT, FOS values were significantly lower due to pore-water pressure. At 1.25H:1V, FOS reduced from 6.767 (1 m) to 1.434 (10 m). Gentler slopes still provided stability, with FOS reaching 2.056 at 10 m for 3.5H:1V.

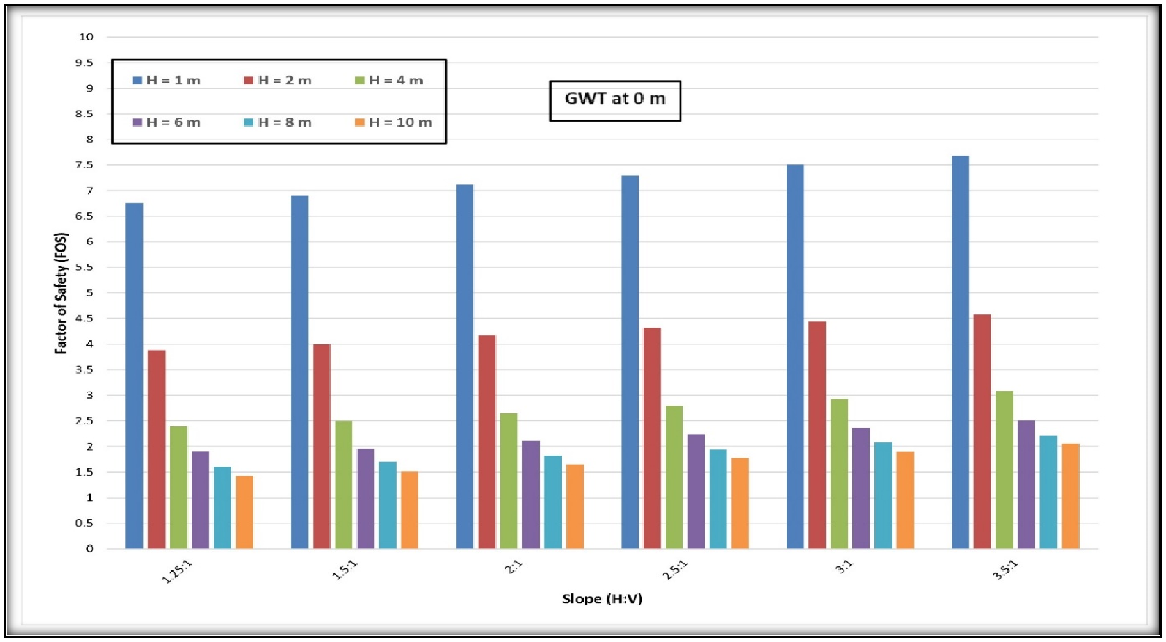

Figure 5Graphical Representation of variation of FOS with Slope Angle and Height (GWT = 0 m)

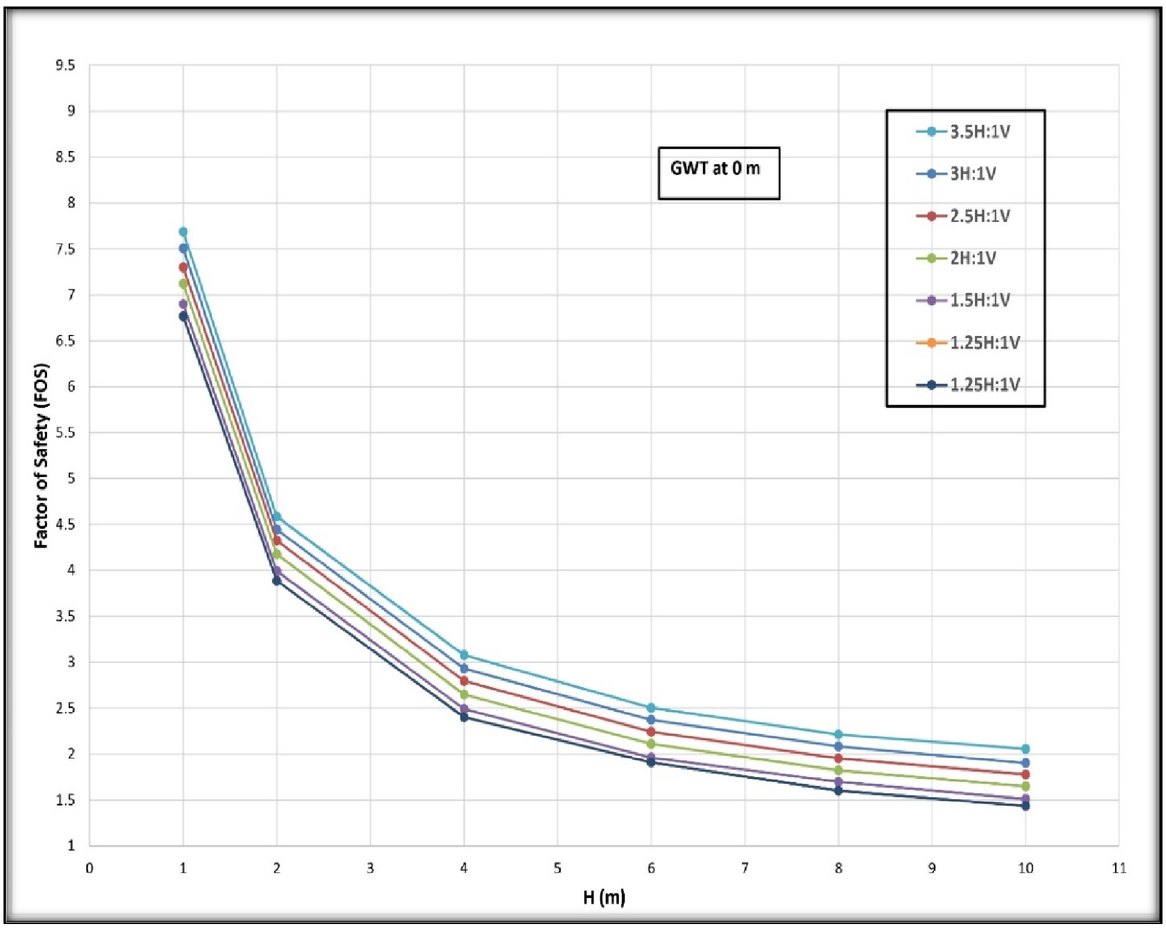

Figure 6Variation of FOS of slope with various slope angles and heights at (GWT = 0m)

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C. Comparison of both groundwater cases

A rise in groundwater level from −4 m to 0 m reduced FOS across all slope ratios and heights. The reduction ranged from ~6% at low embankments to ~14% at higher ones, with maximum reduction observed for gentler slopes due to initially higher stability margins.

Table 3Percentage Reduction in FOS with GWT Rise from -4m to 0m

Height (m)	1.25H:1V	1.5H:1V	2H:1V	2.5H:1V	3H:1V	3.5H:1V
1	6.40%	6.65%	8.69%	9.29%	10.27%	11.20%
2	5.86%	6.51%	8.39%	10.55%	12.72%	13.95%
4	5.51%	6.89%	9.05%	10.96%	12.53%	13.93%
6	5.59%	6.47%	8.89%	11.09%	12.60%	13.61%
8	4.87%	5.34%	8.71%	10.90%	12.08%	13.12%
10	4.65%	6.16%	8.91%	10.52%	11.80%	11.51%

D. Percentage difference between steepest and gentlest slopes

The percentage improvement in FOS between steep (1.25H:1V) and gentle (3.5H:1V) slopes increased with height. At −4 m GWT, improvements ranged from 19.7% (1 m) to 54.5% (10 m). At 0 m GWT, the improvements ranged from 13.6% (1 m) to 43.4% (10 m).

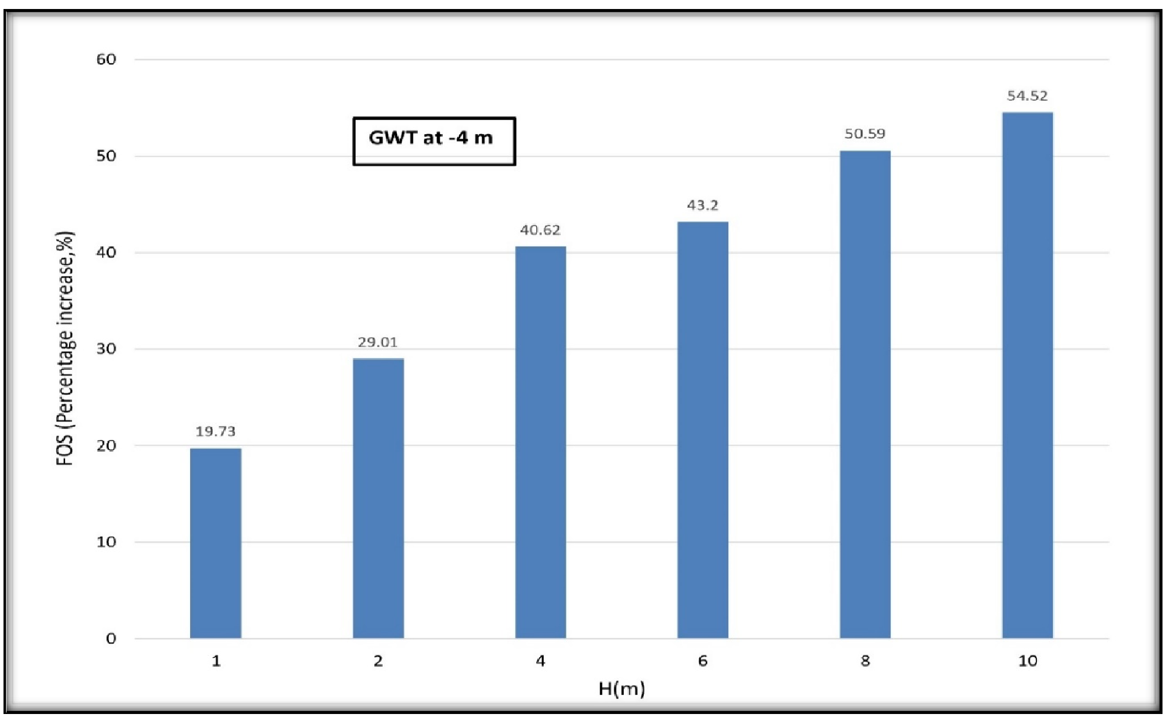

Figure 7Percentage of increase in FOS between the steepest (1.25H: 1V) and gentlest (3.5H: 1V) slopes when GWT is at -4m

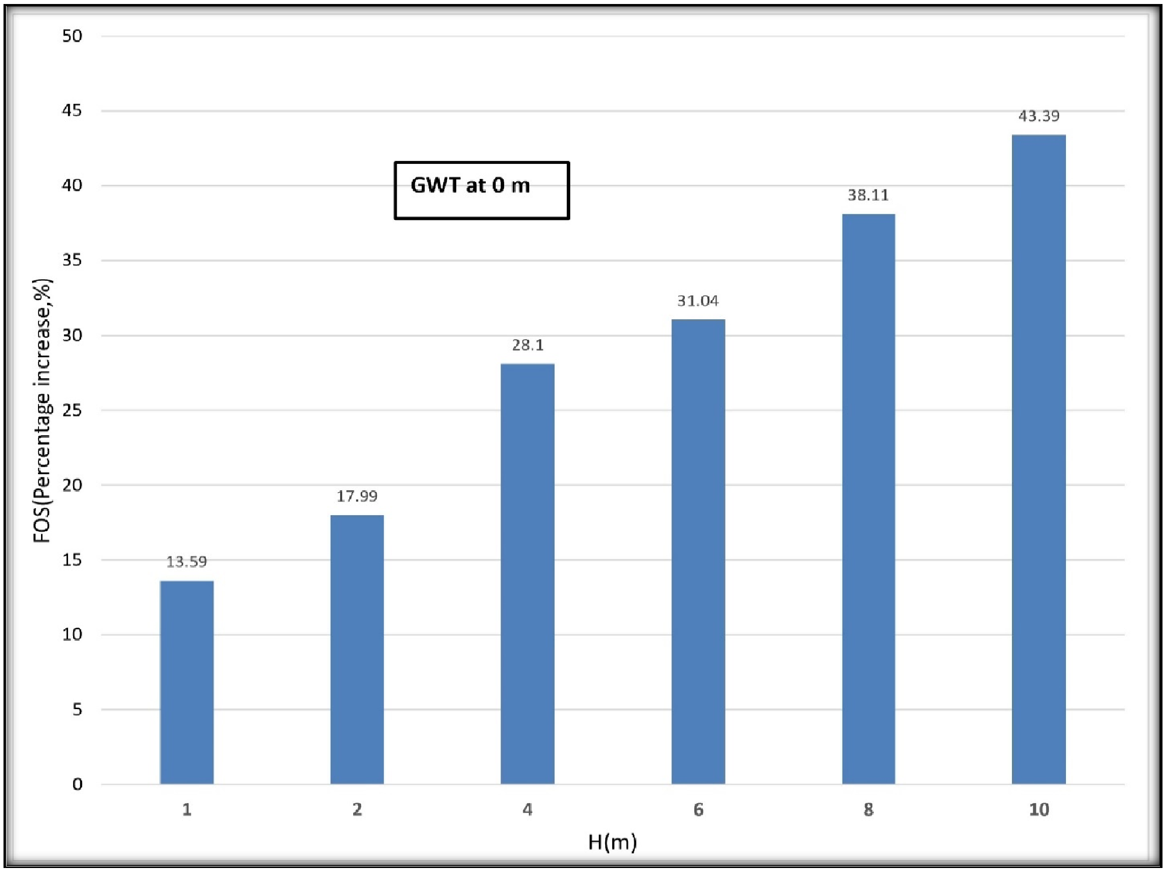

Figure 8Percentage of increase in FOS between the steepest (1.25H: 1V) and gentlest (3.5H: 1V) slopes when GWT is at 0m

V. DISCUSSION

The results confirm that both geometry and groundwater conditions strongly influence slope stability. Gentler slopes enhance FOS by reducing driving stresses, while steeper slopes rapidly lose stability with increasing height. The detrimental effect of groundwater was evident, with up to 35% reduction in FOS when the water table rose to the ground surface. These findings are consistent with prior studies (13,14),which also reported reduced stability with increasing slope height and elevated groundwater conditions. The 3D modelling results highlight the necessity of considering three-dimensional effects in embankment design, as 2D methods tend to oversimplify failure mechanisms.

VI. CONCLUSIONS

1) Gentler slopes (≥3H:1V) provide significantly higher FOS values, particularly for tall embankments.
2) FOS decreases non-linearly with embankment height across all slope ratios.
3) Groundwater rise from −4 m to 0 m reduces FOS by up to 35%, underscoring the need for proper drainage.
4) Percentage improvement from steepest to gentlest slopes reached 54% at −4 m GWT.
5) The study highlights the necessity of adopting flatter slopes and considering groundwater in design for safe highway embankments.

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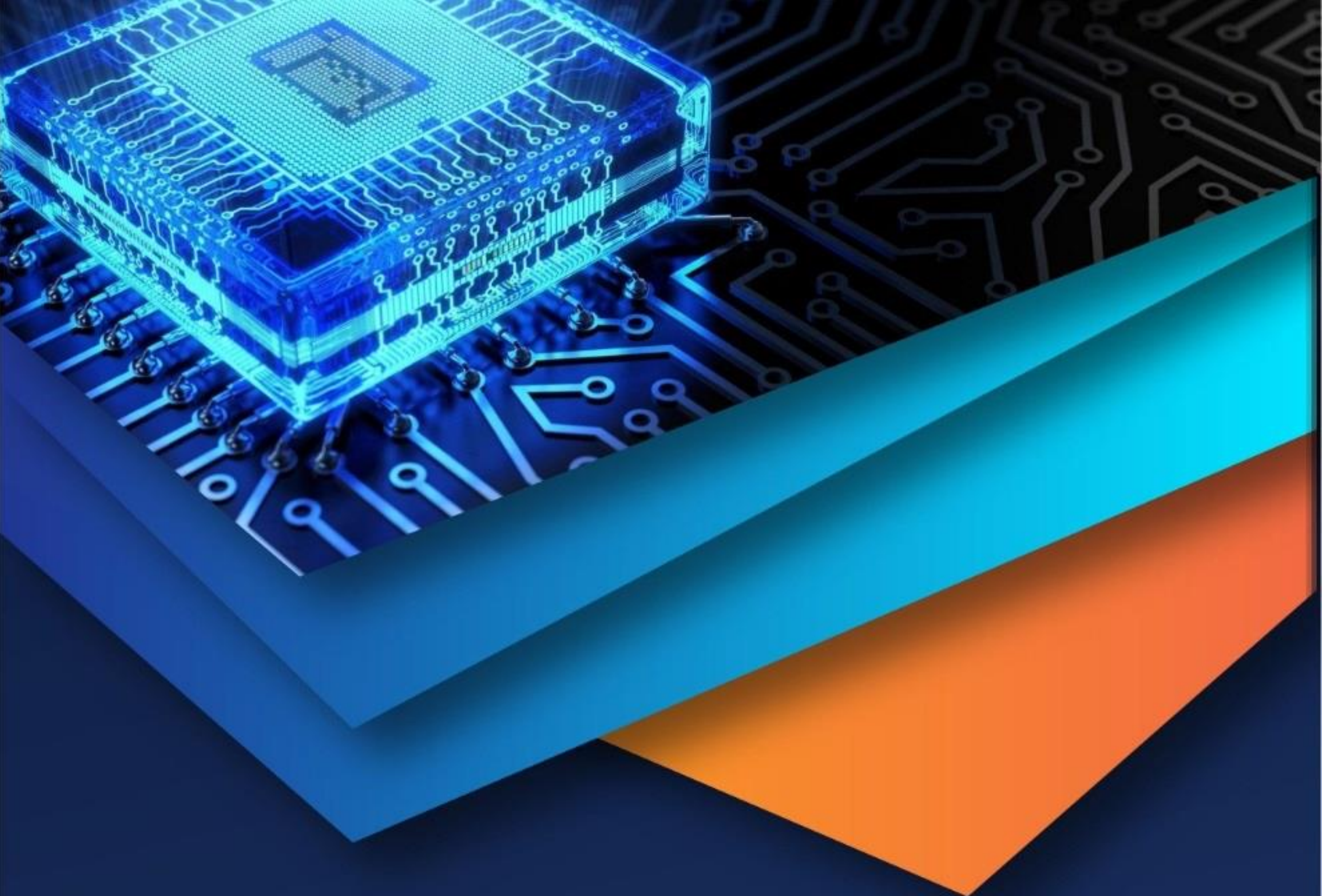

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