Analysis of Stress And Settlement Behavior of Geogrid Reinforced Highway Embankment Under Different IRC Loading

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Abstract:

The growing demand for sustainable and durable transportation infrastructure has highlighted the importance of improving road embankment performance over weak subgrades. Conventional soils often possess low bearing capacity and undergo excessive settlement under repeated traffic loading, leading to pavement deterioration and reduced service life. This study investigates the use of geogrid reinforcement as an effective technique to enhance subgrade strength and control deformation under vehicular loads. A three-dimensional numerical analysis was conducted using PLAXIS 3D to simulate the behavior of geogrid-reinforced embankments subjected to IRC Class A, Class AA, and Class 70R loadings. The embankment model consisted of multiple soil layers with geogrid layers placed at specific depths to improve load transfer and distribution. The simulation involved geometry creation, material definition, geogrid modeling, mesh generation, staged construction, and application of static wheel loads. Soil response was represented using the Mohr–Coulomb and Hardening Soil models. The analysis focused on vertical settlement, stress distribution, and deformation behavior in geogrid-reinforced zones. Results indicated that geogrid inclusion notably reduced settlements and improved stress distribution compared to unreinforced cases. Reinforcement minimized differential settlement and enhanced overall stability under heavy traffic. The findings confirm the effectiveness of geogrid in improving embankment performance, extending service life, and reducing maintenance needs. The study also validates PLAXIS 3D as a reliable numerical tool for optimizing geotechnical design and understanding soil–structure interaction.

Keywords:

Geogrid Reinforcement, Embankment, PLAXIS 3D, IRC Class A, IRC Class AA, IRC Class 70R, Settlement, Stress.

1.Introduction:

The analysis of stress and settlement behavior of geogrid-reinforced highway embankments under different IRC loading conditions is crucial for the safe and economical design of modern transportation infrastructure. Road embankments are subjected to varying magnitudes of vehicular loads depending on traffic type and intensity, which are categorized by the Indian Roads Congress (IRC) as Class A, Class AA, and Class 70R loadings. Class A loading represents normal traffic conditions typically experienced on rural and urban roads, while Class AA and Class 70R loadings simulate heavy commercial and military vehicles that exert higher stresses on the pavement and subgrade. Such heavy loadings often lead to significant settlements and structural distress in conventional unreinforced embankments constructed over weak subgrades.

The incorporation of geogrid reinforcement provides an effective solution by improving the tensile resistance, stiffness, and overall stability of the embankment. Geogrids enhance the load distribution mechanism, reduce stress concentration, and limit vertical deformation under repeated traffic loading. In this study, a three-dimensional numerical analysis using PLAXIS 3D software was carried out to evaluate the response of highway embankments reinforced with geogrid layers at predetermined depths. The simulations considered different IRC loading scenarios to assess their impact on stress distribution, settlement behavior, and overall deformation patterns. The results demonstrate that geogrid inclusion significantly improves performance by minimizing settlements and increasing load-bearing capacity, making it a reliable reinforcement technique for sustainable and durable highway construction

2.Literature review

Shokry (2016) demonstrated through PLAXIS 3D simulations that geogrid layers can reduce vertical settlement and lateral spread by up to 40%, with geogrid stiffness and spacing critically influencing load transfer. Kwon and Tutumluer (2009) confirmed experimentally and numerically that geogrid reinforcement enhances base stiffness, minimizes rutting, and improves load distribution through aggregate interlock. Similarly, Zhang et al. (2024) and Liu et al. (2024) reported that high-stiffness geogrids and optimized placement depths lead to reduced settlements, effective stress redistribution, and improved pavement service life under heavy traffic loads. while Sadeghi (2020) further validated that geogrid reinforcement improves shear strength and stiffness in soft or contaminated ballast layers, reducing deformation under cyclic loading. Önal (2023) compared geocells and geogrids, finding that multiple geogrid layers can approach geocell confinement performance, making them a cost-effective solution for flexible pavement and embankment design. Qian and Zhao (2015) revealed that proper geogrid aperture size and well-graded aggregates enhance interlock and pullout resistance, improving load distribution and reducing lateral deformation. Complementing these, Azim and Sengupta (2021) demonstrated that multiple geogrid layers reduce cumulative settlement and permanent displacement under cyclic wheel loads, with arching effects further enhancing subgrade stability.

3. Methodology

PLAXIS 3D is an advanced finite element software used for three-dimensional analysis of soil–structure interaction and geotechnical stability. Developed at Delft University and now part of Bentley Systems, it models realistic soil and rock behavior under various loading conditions. The software includes advanced constitutive models like Hardening Soil and Soft Soil Creep for accurate deformation prediction. It allows staged construction simulation to replicate real-life sequences such as embankment building or excavation. Automatic and manual meshing options ensure accuracy and efficiency in modeling. PLAXIS 3D supports static, consolidation, and dynamic analyses under drained or undrained conditions. It is widely applied in foundation design, slope stability, tunneling, and ground improvement projects.

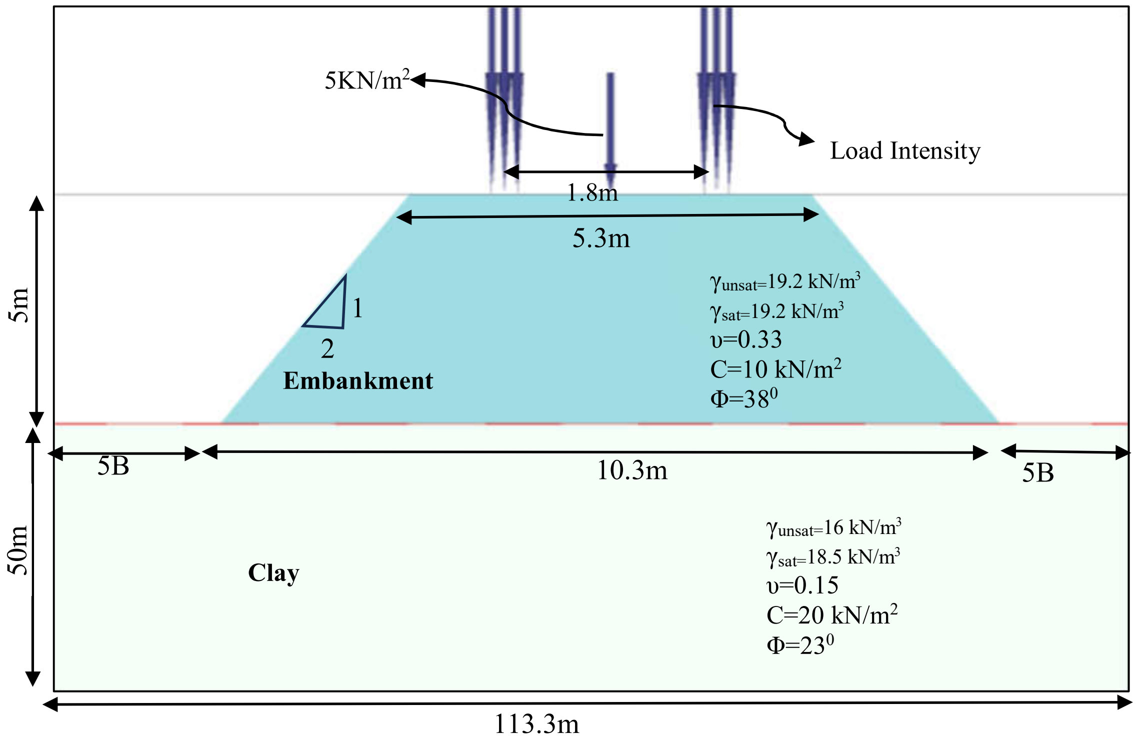

Fig 3.1 Embankment Cross Section with IRC Loading

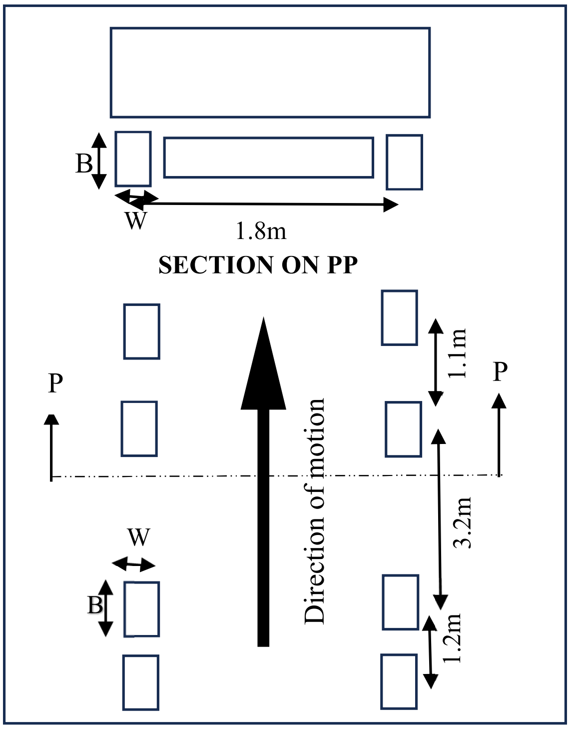

Fig 3.2 Plan of vehicle Loading

Table 3.1 Ground Contact Dimensions for IRC Loading

Classification	Axle load (tons)	Ground Contact Area of Wheel		Load intensity on One Wheel (kN/m^2) (approx.)
		B(mm)	W(mm)	
Class A	11.4	0.25	0.5	912
Class AA	10	0.15	0.3	2220
Class 70R	100	0.86	0.61	1900

Table 3.2 Geogrid location

Number of layers(n)	Placement of Geogrid location from top surface of Embankment
1	1m
2	0.66m,1.32m
3	0.5m,1m,1.5m

Table 3.3 Embankment parameters

Parameter	Specification	Value	Units
Soil model	Model	Mohr-Coulomb	-
Material behavior type	Type	Drained	-
Module of elasticity	E_{ref}	6130	kN/m^2
Unit weight	γ_{unsat}	19.2	kN/m^3
Saturated unit weight	γ_{sat}	19.2	kN/m^3
Poisson's ratio	υ	0.33	-
Cohesion	C	10	kN/m^2
Friction angle	φ	38	degree
Interface strength	R_{intr}	0.9	-

Table 3.4 Clay parameters

Parameter	Specification	Value	Units
Soil Model	Model	Soft soil Creep	-
Drainage type	Type	Undrained A	-
Saturated Unit weight	γ_{sat}	18.5	kN/m^3
Unsaturated Unit weight	γ_{unsat}	16	kN/m^3
Modified swelling index	κ	0.026	-
Modified compression index	λ	0.13	-
Interface strength	R_{inter}	0.9	-
Friction angle	φ	23	degree
Cohesion	C	20	kN/m^2
Poisson's ratio	υ	0.15	-

Table 3.5 Soil Reinforcement Properties

	Parameter	Specification	Value	Units
Geogrid	Material type	-	Elastic	-
	Axial rigidity	EA	1250	kN/m

4. Results and Discussion

This chapter presents the analysis of a road embankment under different IRC loading classes (Class A, AA, and 70R) using Plaxis 3D. It focuses on settlement behavior, stress distribution, and Factor of Safety (FOS). The results show how varying loads affect deformation, stress transfer, and stability. Comparative analysis highlights that higher loads cause greater settlement and lower safety. Overall, the study demonstrates the effectiveness of geogrid reinforcement and numerical modeling for embankment design.

4.1 Results for IRC Class A Loading

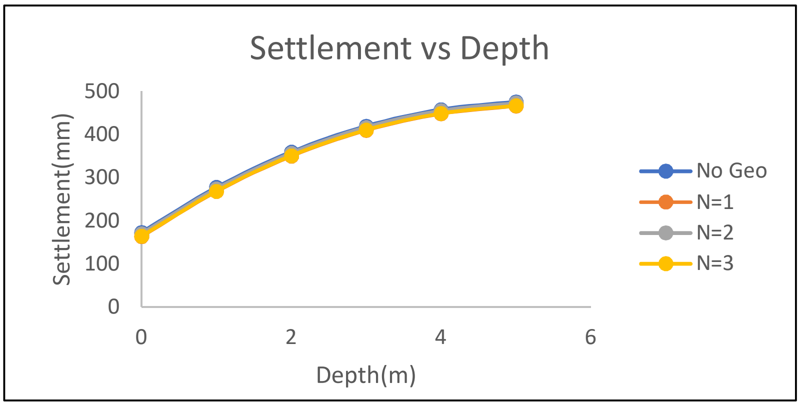

Fig 4.1 Settlement Vs Depth for Class A loading

Fig 4.1 shows that settlement decreases with more geogrid layers. The unreinforced embankment shows the highest settlement, while three layers give the lowest. Geogrids improve soil stiffness by limiting lateral movement and distributing loads evenly, leading to reduced deformation. The maximum reduction occurs near the surface, showing that proper layer placement enhances performance.

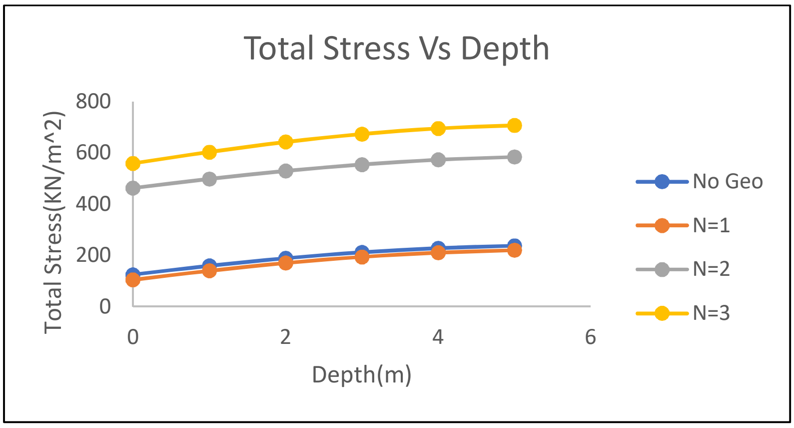

Fig 4.2 Total Stress Vs Depth for Class A loading

Fig 4.2 shows that total stress increases with more geogrid layers. The unreinforced embankment has the lowest stress, while three layers show the highest due to improved soil confinement and load distribution. Geogrids strengthen the soil, allowing it to resist higher loads and distribute stress more effectively. Overall, increasing geogrid layers enhances the soil's load-bearing capacity and stability.

4.2 Results for IRC Class AA Loading

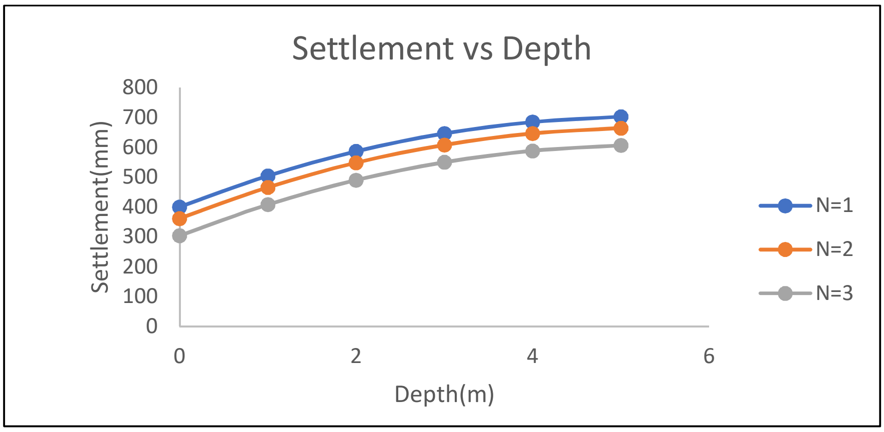

Fig.4.3 Settlement vs Depth of Class AA loading

Fig 4.3 shows that settlement decreases as the number of geogrid layers increases, proving their effectiveness in improving soil stability. The unreinforced embankment shows the highest settlement, while three layers give the lowest. Geogrids enhance tensile strength, limit lateral spreading, and improve load distribution. The greatest improvement occurs near the surface, indicating stronger confinement and reduced deformation with more layers.

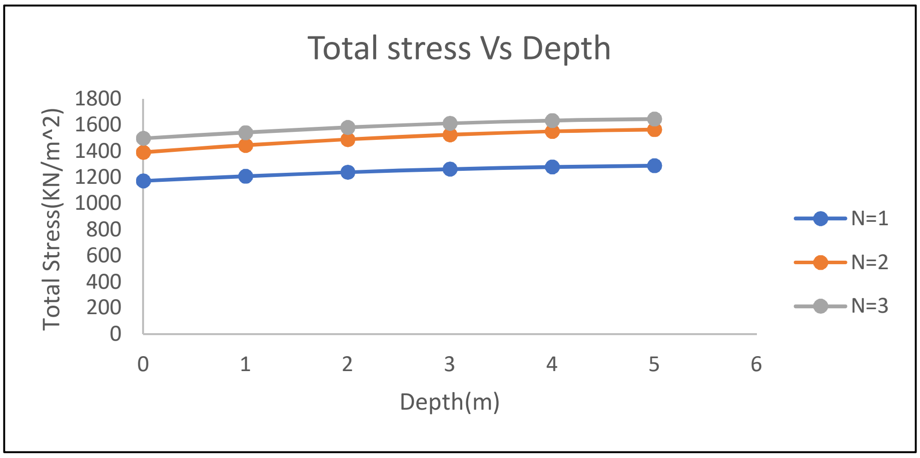

Fig 4.4 Total Stress Vs Depth of Class AA loading

Fig 4.4 shows that total stress increases with more geogrid layers. Without geogrid, the embankment fails due to poor stability. With one layer, stress begins to distribute evenly, while two and three layers provide higher and more uniform stress, indicating better confinement and strength. Three layers offer maximum load-carrying capacity and stability, proving the effectiveness of geogrid reinforcement.

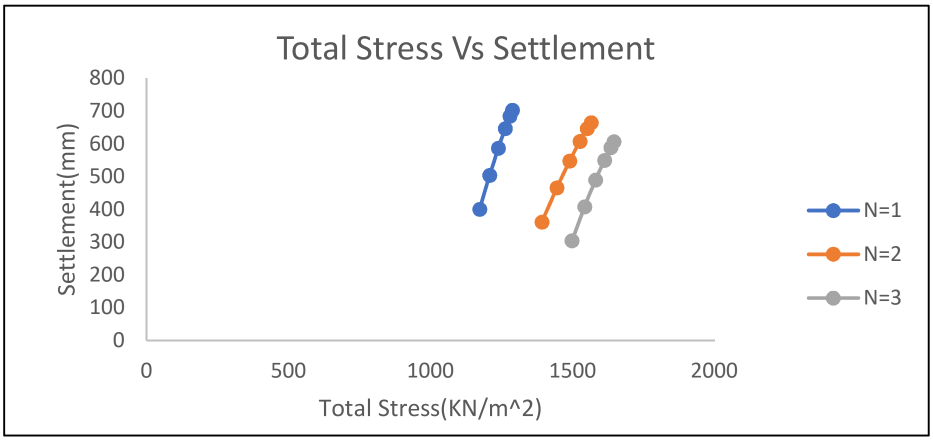

Fig 4.5 Total Stress Vs Settlement of Class AA loading

Fig. 4.5 shows that without geogrid, the embankment collapses due to excessive deformation. With one layer, settlement slightly decreases, and with two layers, stability and load distribution improve further. Three layers give the best performance, showing higher stress and lower settlement due to increased stiffness and confinement. Overall, geogrid reinforcement effectively prevents collapse and enhances embankment stability.

4.3 Results for IRC Class 70R Loading

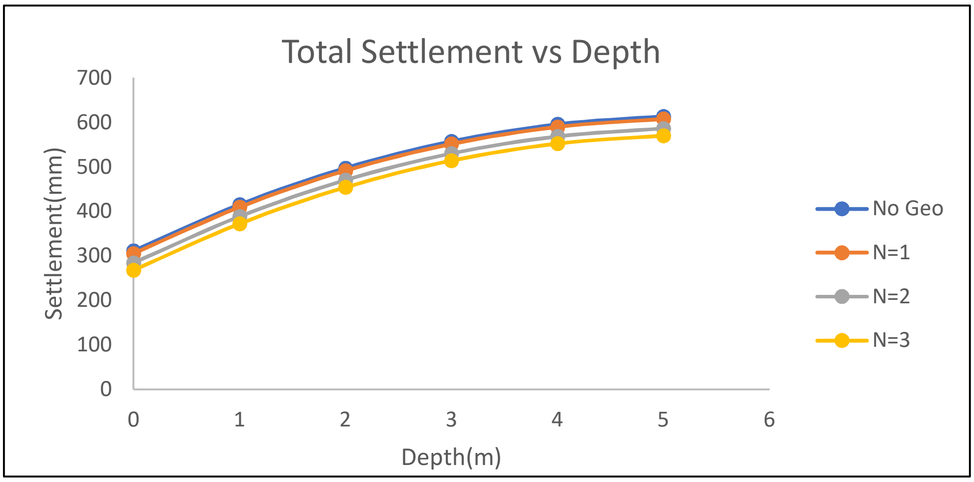

Fig 4.6 Settlement vs Depth of Class 70R Loading

Fig 4.6 shows that settlement increases with depth for all cases under Class 70R loading but is highest without geogrid. Adding one, two, and three geogrid layers progressively reduces settlement by improving load distribution and soil strength. Geogrids confine the soil, control deformation, and enhance bearing capacity, resulting in a more stable and durable embankment.

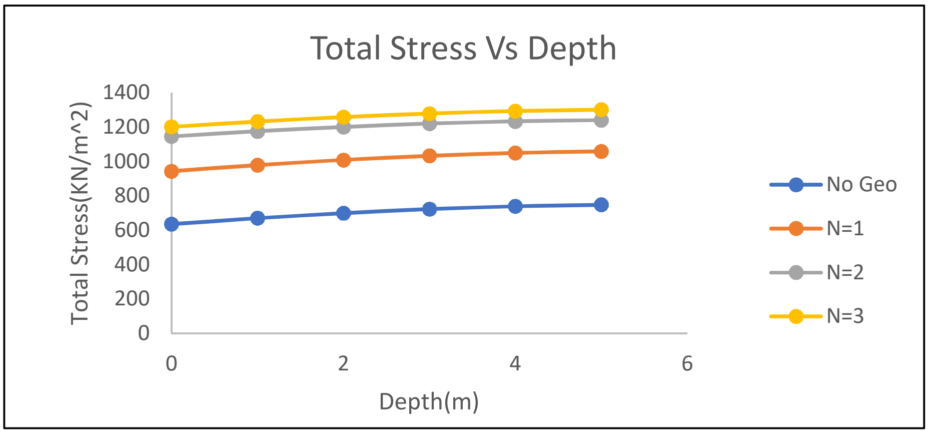

Fig 4.7 Total Stress Vs Depth of Class 70R Loading

Fig 4.7 shows that total stress increases with depth under Class 70R loading. Unreinforced soil has the lowest stress, while geogrid layers enhance load-carrying capacity. The curves for two and three layers are nearly identical, indicating that two layers provide optimal reinforcement. Overall, geogrid inclusion improves soil strength and stability, with two layers offering the most efficient performance.

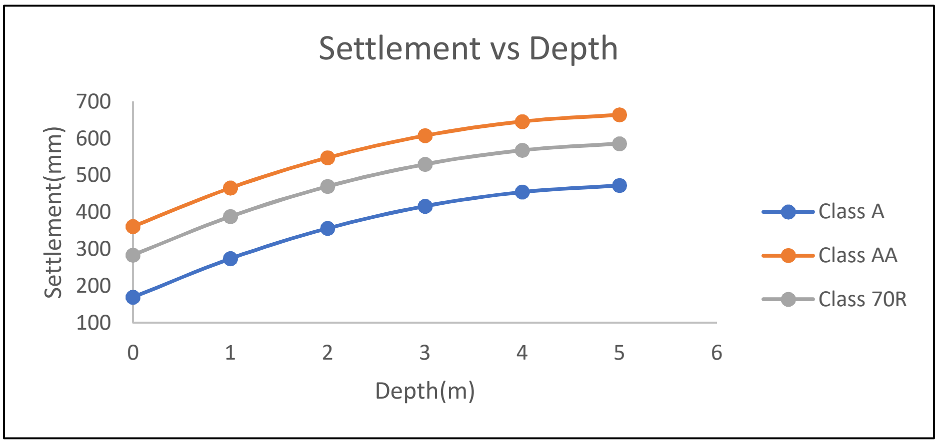

Fig 4.8 Depth vs Settlement of IRC Class Loading

Fig. 4.8 shows that settlement is highest under Class AA loading, intermediate for Class 70R, and lowest for Class A. Settlement is greatest near the surface and decreases with depth due to reduced vertical stress. Higher load intensities cause greater deformation, emphasizing the need for geogrid reinforcement or soil improvement under heavy loading for embankment stability.

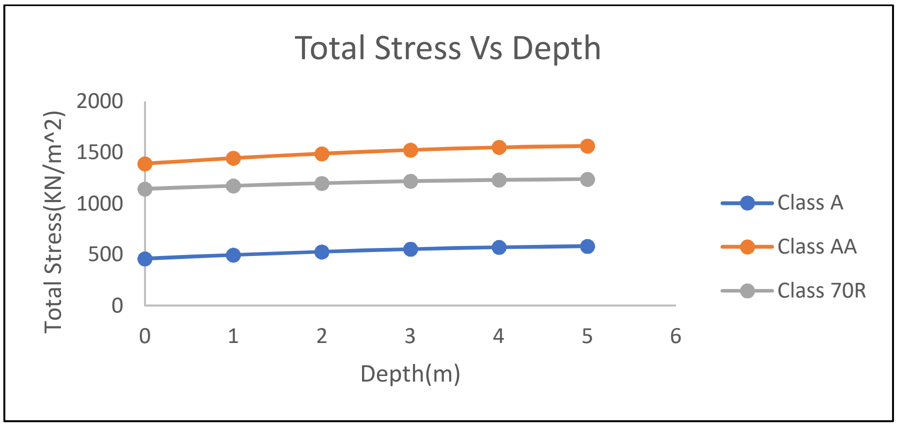

Fig 4.9 Total Stress Vs Depth for IRC Class Loading

Fig. 4.9 shows that total stress is highest for Class AA, intermediate for Class 70R, and lowest for Class A at the surface. Stress decreases with depth for all classes due to load dispersion, with similar rates of reduction. The figure highlights that heavier loads induce higher stresses throughout the embankment.

5. Conclusions

1. Settlement reduced notably with geogrid layers, showing maximum improvement under three-layer reinforcement.

2. Total stress distribution became more uniform, increasing soil strength and reducing deformation.

3. The factor of safety improved across all load classes, with two to three geogrid layers giving stable performance.

4. Optimum results occurred with two geogrid layers and EA between 1250–2500 kN/m, ensuring strength, stability, and economy.

6. References

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