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Slope Stability Analysis for Highway Embankment using FEM

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Abstract:
Evaluation of slope stability is one of the most important topics in geotechnics. Highway embankments are critical structural elements in road construction and ensuring their stability is essential to prevent landslides, erosion and other failures that could compromise road safety and function. In the present study, slope stability analysis of highway embankment has been done by numerical technique finite element method using Geo Studio. Soil samples are collected and geotechnical properties have been evaluated by performing laboratory tests as per Indian standards. Finite element modelling of slopes is done in GeoStudio. Slope stability analysis have been performed and factor of safety (FOS) is calculated. Various parametric studies have been carried out depending on variations in geotechnical parameters and geometry of slopes. It is observed that FOS is within permissible limits.

Keywords: **Finite Element Method, Stability of Slopes, Embankment, Factor of Safety.**

1. INTRODUCTION

The assessment of slope stability is a widely explored subject in geotechnics. Practically, it spans tasks such as initial assessments of potentially hazardous zones, specialized structural designs, and analysing failures through back calculations. Theoretical discussions delve into developing new methodologies and critically evaluating established practices. Road slope stability holds critical significance in design, requiring rigorous analysis and evaluation, especially for steep embankments. Geotechnical methods rely heavily on accumulated expertise with various soil and rock types to determine the parameters influencing slope stability. These embankments are critical structural elements in road construction, and ensuring their stability is essential to prevent landslides, erosion, and other failures that could compromise road safety and function. Here's a breakdown of the process:

i. Highway Embankments and Slope Stability: Embankments are raised structures made of soil or other materials built to support a road or railway. These embankments can be prone to failure due to factors like weather conditions, soil type, external loads (traffic), and groundwater flow. Slope stability refers to the resistance of a slope to sliding or collapse. Slope failure can occur if the shear stress exceeds the shear strength of the soil, leading to landslides or slumping, which are hazardous to infrastructure.

ii. Finite Element Method (FEM): FEM is a numerical technique used to solve complex engineering problems, especially those involving structural, thermal, and fluid dynamics analysis. It divides a large system into smaller, simpler parts called finite elements.

1.1 Application of FEM in Slope Stability: The process of performing slope stability analysis for a highway embankment using FEM typically involves the
Following steps:
•Modeling the Embankment and Soil Layers
•Boundary Conditions
•Loading Conditions
•Analysis of Shear Strength
•Safety Factor Calculation
•Failure Mechanisms

1.1.1 Advantages of Using FEM for Slope Stability Analysis

• Accuracy and Detail: FEM provides a more accurate and detailed analysis compared to traditional methods as it can handle complex geometries and varying material properties.

• Non-linear Analysis: FEM allows for non-linear material behavior, which is important for modeling soil-structure interactions more realistically.

• Customization: It can model different types of loads (e.g., dynamic loads, traffic, seismic forces), making it highly adaptable for real-world conditions.

• Optimization: FEM helps engineers optimize the embankment design to improve safety and cost-efficiency by testing various scenarios and adjusting design parameters.

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1.2 Geostudio: GeoStudio is a comprehensive suite of software tools designed for geotechnical and geo-environmental modeling. It is widely used by engineers, geologists, and researchers to analyze soil, rock, and groundwater conditions in a variety of civil engineering and environmental projects. Developed by Seequent, GeoStudio offers an integrated platform for solving complex geotechnical problems through numerical analysis.

1.2.1 Key Features of GeoStudio-

1.Modular Design: GeoStudio consists of several modules, each tailored for specific types of analyses.

2. Integrated Analysis: Modules are fully integrated, allowing users to conduct multi-disciplinary analyses.

3.Graphical User Interface (GUI):GeoStudio features an intuitive, user-friendly GUI for creating models, visualizing results, and refining designs.

4.Material Models: A wide range of material models is available to simulate soil and rock behavior, including linear, non-linear, and unsaturated soil mechanics.

5.Visualization: Advanced tools for visualizing simulation results in 2D and 3D, including contours, vectors, and graphs, help interpret results effectively.

6.Customizability: Users can define custom boundary conditions, material properties, and geometry to match real-world conditions.

1.3 Factors Influencing Slope Stability: Several factors contribute to slope stability, including slope geometry, dynamic forces, soil cohesion, internal friction angle, lithology, and groundwater conditions.

1.4 Factor of Safety (FOS): Slope stability is determined by various parameters, including the soil's physical and mechanical characteristics. Physical properties such as water content, soil composition, and texture play a crucial role. Meanwhile, mechanical properties, including shear strength, cohesion, and internal friction, are critical for stability assessment.

Guidelines for the factor of safety (FOS) for slopes are summarized in Table I. The FOS is a measure of stability expressed as the ratio of resisting forces to driving forces. Mathematically, it is represented as:

$$\mathbf{FOS = S/r}$$

Table 1: Details of Slope with FOS

Factor of safety (FOS)	**Details of slope**
>1.4	Considered to be satisfactory for the dams
1.25-1.40	Considered to be satisfactory for routine cuts and fills but may be questionable for dams, or where failure would be catastrophic
1.0-1.25	Considered to be questionable for safety
<1.0	Considered to be unsafe

1.5 Types of Slope Failure: Slopes can experience various types of failure, including planar failure, wedge failure, circular failure, toppling failure, and two-block failure.

1.6 Angle of Internal Friction: The angle of internal friction is the angle formed between the resultant force and the normal force at the point of complete failure caused by shear stress. The material must be capable of resisting shear stress. Key factors influencing this angle include particle roundness, particle size, and the quartz content in the soil. A higher angle of internal friction indicates a steeper slope.

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1.7 Cohesion: Cohesion refers to the resistance of a material to deformation or cracking under applied forces. In soils, cohesion arises due to electrostatic forces between particles or pore water pressure, often influenced by negative capillary tension or external loading. Slopes with lower cohesive forces are typically less stable. Factors affecting cohesion include friction, particle viscosity, grain cementation by calcite or silica, artificial reinforcements, water content, and other external conditions.

2. LITERATURE REVIEW:

Slope stability is a critical consideration in geotechnical engineering, particularly for infrastructure projects such as highways, where embankments are essential for road construction over uneven terrain. Slope instability in embankments can result in significant hazards including landslides, road closures, and economic losses. Therefore, understanding the behavior of highway embankments under various loading conditions and environmental factors is crucial for safe and efficient design.

Traditional slope stability analysis methods, such as limit equilibrium methods (LEM), have been commonly employed for decades to assess the safety of slopes. However, with the advancements in computational tools, more sophisticated techniques such as Finite Element Analysis (FEA) have gained prominence for evaluating slope stability, especially for complex and heterogeneous soil profiles. This section reviews the evolution of slope stability analysis techniques, focusing on the application of FEA to highway embankment design and analysis.

2.1 Finite Element Analysis in Slope Stability

Finite Element Analysis (FEA) has emerged as a powerful tool for modeling complex slope stability problems, offering a more accurate and detailed representation of soil behavior, geometry, and boundary conditions. Unlike LEM, which assumes a predefined failure surface, FEA allows for the simulation of the entire embankment system, taking into account the nonlinear behavior of materials and the influence of different factors like pore water pressure, soil consolidation, and external loading.

One of the key advantages of FEA is its ability to model heterogeneous soils, varying water levels, and boundary conditions more realistically. Naylor et al. (2016) applied FEA to study the impact of different embankment materials on slope stability under heavy traffic loading. The study demonstrated that the use of FEA allowed for a more detailed understanding of how variations in embankment material composition (e.g., soil vs. geosynthetics) influenced the safety factor and failure modes of the slope.

2.2 Applications in Highway Embankments

Highway embankments often present unique challenges in slope stability analysis due to the dynamic loadings from traffic, varying environmental conditions, and the need for durable structures with long service lives. The study highlighted the importance of modeling the embankment construction process (e.g., sequential loading and consolidation) and the significant influence of traffic-induced dynamic loads on slope stability. The results emphasized the advantage of FEA in capturing time-dependent behaviors such as soil consolidation and long-term settlement, which are crucial for highway embankment design.

2.3 Integration of Geotechnical Data with FEA

The accuracy of FEA in slope stability analysis heavily depends on the input data, which includes soil properties, groundwater conditions, and loadings. The integration of geotechnical site investigation data, such as borehole logs, laboratory test results, and in-situ measurements, is essential to improve the reliability of FEA models. Schneider et al. (2017) discussed the importance of integrating geophysical data and numerical modeling techniques in slope stability analysis for highway embankments. The authors argued that proper site characterization, combined with FEA, significantly enhances the predictive capabilities of slope stability assessments.

2.4 Challenges and Future Directions

Despite the advantages of FEA in slope stability analysis, several challenges remain. First, the complexity of FEA models requires significant computational resources, especially when dealing with large-scale embankments or highly detailed models. Furthermore, accurate soil modeling remains a challenge due to the inherent variability and uncertainty of geotechnical properties. The choice of constitutive models, such as the Mohr-Coulomb or Cam-Clay models, can significantly influence the results and should be carefully selected based on site-specific conditions.

Future research is likely to focus on improving the efficiency of FEA methods through the development of more advanced numerical techniques, such as meshless methods or discrete element methods (DEM), which may reduce computational costs while maintaining accuracy. Additionally, the integration of FEA with machine learning approaches may help in automating the process of model calibration and sensitivity analysis, making slope stability assessments more accessible and efficient.

2.4 OBJECTIVE OF THE STUDY

- Evaluation of geotechnical properties of collected soil samples.
- Development of FEM model on varying side slopes.
- Evaluation of factor of safety of slopes by varying methods
- Comparative analysis of the results obtained.

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3. ANALYSIS AND RESULTS:

Table 2: Properties of Soil at Location 1

Property (Location 1)		Value	IS Standard
Atterberg's Limits			IS:2720 (Part-3)-1981
a.	Liquid limit (%)	34.35	
b.	Plastic limit (%)	19.30	
c.	Plasticity index (%)	15.04	
Grain size distribution			IS:2720 (Part-4)-1985
a.	Gravel fraction (%)	14.93	
b.	Sand fraction (%)	24.59	
c.	Silt fraction (%)	60.48	
d.	Clay fraction (%)	…….	
Specific Gravity by Density Bottle		2.06	IS:2720 (Part-3)-1981
Heavy Compaction	Optimum Moisture Content (OMC) (%)	12.9	IS:2720 (Part-8)-1983
	Maximum Dry Density (MDD) (g/cc)	1.095	

Table 3: Properties of Soil at Location 2

Property (Location 2)		Value	IS Standard
Atterberg's Limits			IS:2720 (Part-3)-1981
a.	Liquid limit (%)	28.34	
b.	Plastic limit (%)	22.98	
c.	Plasticity index (%)	5.36	
Grain size distribution			IS:2720 (Part-4)-1985
a.	Gravel fraction (%)	5.6	
b.	Sand fraction (%)	56.8	
c.	Silt fraction (%)	37.6	
d.	Clay fraction (%)	……	
Specific Gravity by Density Bottle		2.68	IS:2720 (Part-3)-1981
Heavy Compaction	Optimum Moisture Content (OMC) (%)	15.6	IS:2720 (Part-8)-1983
	Maximum Dry Density (MDD) (g/cc)	1.836	
CBR (%) Soaked(96 hour)		3.5	IS:2720 (Part-16)-1987
Direct Shear Test		C=0.0302 Phi=9.253	IS:14001:1996

3.1 CBR Test as per IS - 2720-16 (SOAKED)

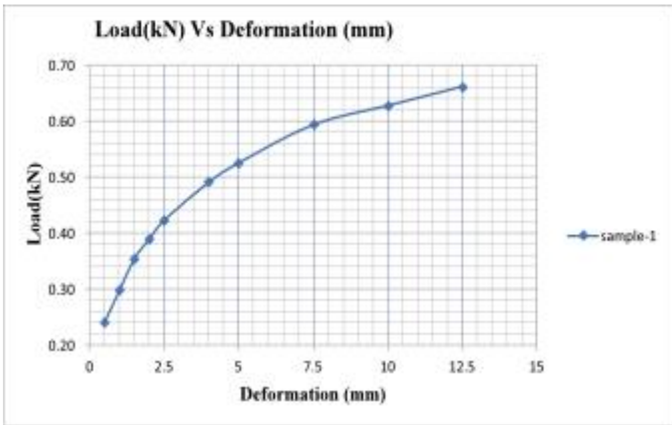

Fig.1 Graph between load and deformation

3.2 Direct Shear Test

Table 2: Properties of Soil (DST)

LOCA	Load	Displacement1(mm)	Displacement 2(mm)	Shear Load(KN)	Normal Stress (Kg/cm2)	Shear Stress(Kg/cm2	Value of C	Value of Phi
2	0.5	13.61	13.61	0.041	0.5	0.1162	0.0302333	9.253268391
	1	13.88	13.88	0.064	1	0.1813		
	1.5	14.27	14.27	0.098	1.5	0.2777		

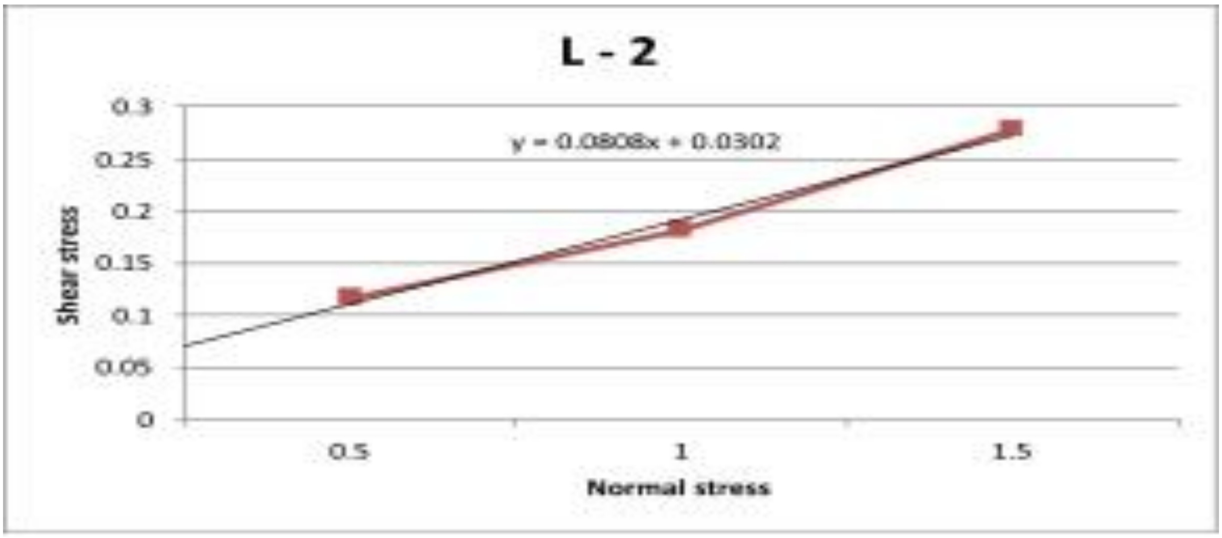

Fig.2 Graph between Shear Stress and Normal Stress

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3.3 Geostudio Software working

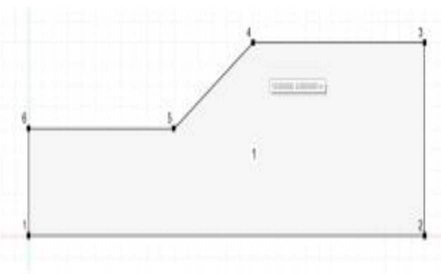


Fig.3 Region 1

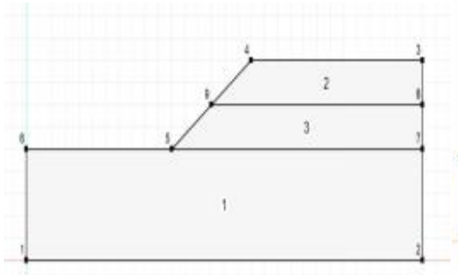


Fig.4 Spliting Region

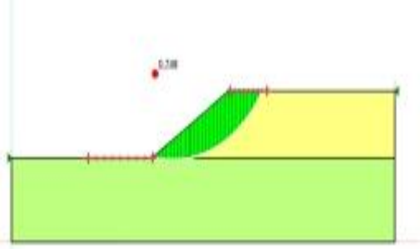


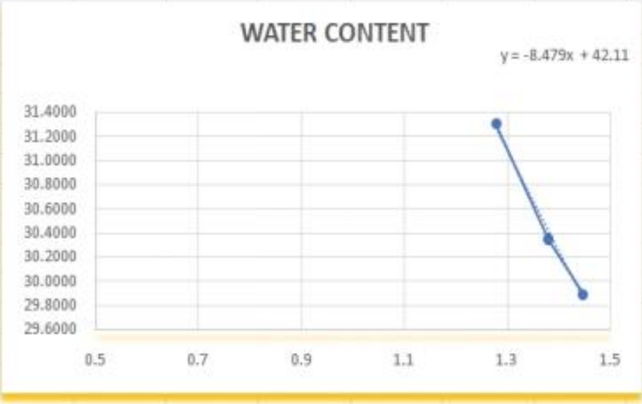
Fig.4 slip surface

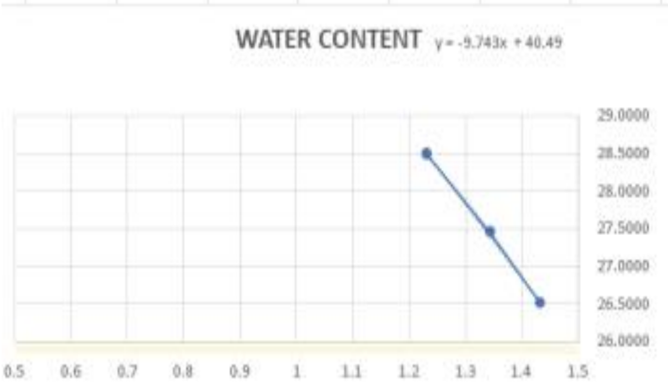
LIQUID LIMIT [LOCATION -1]

Cont. name	empt.wt of cont.	wt. of cont. +wet soil	wt.of cont.+dry soil	no. of blows (n)	$Log_{10}(n)$	water content
109	29.556	40.076	37.568	19	1.278754	31.3030
Q7	13.936	23.555	21.316	24	1.380211	30.33875
AZ	12.206	22.631	20.232	28	1.447158	29.89036
				25	1.39794	34.35012

LIQUID LIMIT [LOCATION -2]

Cont. name	empt.wt of cont.	wt. of cont. +wet soil	wt.of cont.+dry soil	no. of blows (n)	$Log_{10}(n)$	water content
PK-11	30.903	42.428	39.873	17	1.230449	28.4838
ARSV	32.328	43.212	40.867	22	1.342423	27.46223
Z-0	28.692	39.841	37.504	27	1.431364	26.52065
				25	1.39794	28.34405





Location1-plastic limit

Cont. name	empt.wt of cont.	wt. of cont. +wet soil	wt.of cont.+dry soil	water content
H-10	16.508	17.458	17.215	34.37058
M-2	15.905	17.161	17.11	4.232365
				19.30147
		IP	15.04865	

Location2-plastic limit

Cont. name	empt.wt of cont.	wt. of cont. +wet soil	wt.of cont.+dry soil	water content
H-26	14.236	15.327	15.163	17.69148
M-23	16	17.216	16.948	28.27004
				22.98076
IP	5.363292			

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4. CONCLUSION:

Finite Element Analysis has proven to be an effective tool for assessing slope stability in highway embankments, offering a more comprehensive approach than traditional limit equilibrium methods. The ability of FEA to model complex material behavior, external loading, and environmental conditions makes it invaluable for modern infrastructure projects. While challenges such as computational costs and data uncertainties persist, ongoing research and technological advancements hold the potential to further improve the accuracy and applicability of FEA in slope stability analysis. As highway embankments continue to be a crucial part of transportation infrastructure, the integration of advanced numerical techniques like FEA will play an increasingly important role in ensuring their safety and longevity.

5. REFERENCES:

1. Singh, D., & Kumar, V. (2021, November). Slope Stability Analysis of Highway Embankment by Using GEO5 Software. In Indian Geotechnical and Geoenvironmental Engineering Conference (pp. 249-257). Singapore: Springer Nature Singapore.
2. Kadlicek, T., & Masin, D. (2023). Surface layer method for analysis of slope stability using finite elements. Computers and Geotechnics, 164, 105799. Al-Shukur, A.H. , Al-Qaisi, A.Z. and Al-Rammahi, A.M. (2018), “Nonlinear analysis of water–soil–barrage floor interaction ” MATEC Web of Conferences 162, 03013 (2018),
3. Hutton, David V.: Fundamentals of Finite Element Analysis. Boston McGraw-Hill, (2004).
4. Kamal, U. D., Ashish, and Ranjan, R.: Finite Element Analysis of Rigid Plane Frame and its application in Building Structures, Proceedings of National Conference on Recent Advances in Structural Engineering (NCRASE-2020), NIT Jamshedpur, India, Page 29-33, August 21-22, (2020).
5. Selvadurai, A.P.S.: Elastic Foundation of soil-foundation interaction. Developments in Geotechnical Engineering, Vol 17, Elsevier scientific publishing company, New York (1979).
6. Bureau of Indian Standards, Criteria for Earthquake Resistant Design of Structures, IS 1893 (PART 1): 2016 (Sixth Revision), New Delhi.
7. Paz, Mario, Structural Dynamics: Theory and Computation, CBS publishers and distributors, Journal of Japan Society of Civil Engineers 73(4), 109-114.
8. Agarwal, Pankaj and Shrikhande, Manish (2010), Earthquake Resistant Design of Structures, PHI Learning Private limited, New Delhi, 1-87.
9. International Journal of Multidisciplinary Research and Development Online ISSN: 2349-4182, Print ISSN: 2349- 5979, Impact Factor: RJIF5.72
10. Mamat, R. C., Ramli, A., Kasa, A., Razali, S. F. M., & Omar, M. B. H. C. (2021). Artificial neural networks in slope of road embankment stability applications: a review and future perspectives. International Journal of Advanced Technology and Engineering Exploration, 8(75), 304.