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Next-Generation Computational Methods for Soil Strength Analysis in Highway Subgrades

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***Abstract*— The strength of soils is an important factor with regards to the performance and longevity of the highway subgrades. At times, the traditional approaches used to assess soil properties, including laboratory and empirical correlations, have been lengthy, expensive as well as being restricted in predictive ability. As computational technologies are evolving, new approaches- next- generation approaches- have also come about to be useful in analyzing soil strength including. The paper examines how advanced methods of calculation can be used to predict. The study compares effectiveness, accuracy, and reliability of those approaches with the traditional ones. Findings show that computational models are a lot more effective than other prediction techniques that consume a lot of time in testing and hence this makes them very appropriate in the current engineering of highways**

***Index Terms*— Soil Strength, Highway Subgrades, Machine Learning, Artificial Neural Networks, CBR Prediction, Computational Intelligence, Geotechnical Engineering.**

I. INTRODUCTION

Design and building of the highway subgrades should include good knowledge of the strength properties of the soil since these are the key determinants of the performance of the pavement, its load-bearing and stability in the long-run. Correspondingly, the traditional methods to test the strength of soils include laboratory and field tests plate load tests and triaxial tests.

Although these are certain methods of giving results that are accurate, they are usually labor consuming, time consuming with the help of specific devices. The last years were marked by development of computational technologies that have changed the sphere of geotechnical engineering. based methods has helped engineers to more effectively and accurately predict soil behavior. These new-generation computational procedures utilize massive data and advanced algorithms that are relevant in modeling nonlinear and complicated relationships at the property of soils. The force of the increasing need of sustainable and cost-efficient development of the infrastructure, especially on developing states, such as India, has also reiterated the necessity of the fast and effective soil analysis methods. Along with decreasing the need to test models on a large scale, computational models also improve decision-making in designing highway projects.

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II. Literature Review

It has been proven that computational techniques are useful in estimating soil strength parameters in several studies. Ghorbani et al. (2018) used the model of (ANN) to estimate the California Bearing Ratio (CRB) of soil and obtained much better accuracy than other methods with regression. Their results showed that ANN had the ability to deduce the nonlinear associations among soil parameters

Networks process of forecasting shallow foundation settlements. Their study determined that ANN models are better than the traditional e empirical techniques particularly when it comes to complex geotechnical situations.

Bui et al. (2019) suggested a machine learning scheme concerning the mixture of the algorithms to forecast the strength of soil. Their model was shown to be more reliable and precise showing that hybrid techniques have the potential to be used in geotechnical applications.

Han et al (2012) offered a rigorous groundwork on data mining methods with the aim of highlighting the relevancy of the method in eliciting significant patterns in huge data sets. These methods are the basis of the current computational techniques in the analysis of soil.

Some standard guidelines on are given in (IRC:372012) and these guidelines depend on the proper evaluation of the soil strength. Nevertheless, these principles rely on the traditional methods of testing, which shows the lack, which can be addressed with the help of the computational ones. services was introduced by Moayedi et al. (2020) and proves the prediction modeling of soil properties.

The recent research by Khawaja et al. (2024) was aimed in the form of genetic algorithms and ANN. Their results revealed that hybrid models get much better results than single-model methods with regards to prediction accuracy.

A. Objectives of the research work

- The objective of the study was to determine the predictive power of the next – generation computational techniques on forecasting soil strength parameters of highway subgrades.
- To compare performance and accuracy of computational models over conventional tests of soil such as the California Bearing Ratio (CRB) test.
- The objective of the study is to come up with a well-developed predictive framework to be used in estimating subgrade soil properties to be used in designing and construction practice in the highways.

III. Analysis of the Study

Table I: Input Parameters used for Soil Strength Prediction

S. No.	Parameter	Symbol	Unit	Description
1	Moisture Content	MC	%	Water content present in soil
2	Dry Density	DD	g/cm³	Compacted density of soil
3	Liquid Limit	LL	%	Water content at liquid state
4	Plastic Limit	PL	%	Water content at plastic state
5	Plasticity Index	PI	%	Difference between LL and PL
6	Grain Size Distribution	GSD	%	Particle size variation
7	Specific Gravity	SG	-	Ratio of soil density to water

Table II: Comparison of Traditional and Computational Methods

Criteria	Traditional Methods	Computational Methods
Time Requirement	High	Low
Cost	Expensive	Cost-effective
Accuracy	Moderate	High
Data Handling	Limited	Handles large datasets
Complexity Handling	Low	Excellent for nonlinear problems
Field Dependency	High	Low

Table III: Performance Evaluation Of Models

Model Type	Accuracy (%)	RMSE	R^2 Value	Prediction Capability
Linear Regression	72	6.5	0.70	Moderate
Artificial Neural Network (ANN)	89	3.2	0.91	High
Support Vector Machine (SVM)	85	4.1	0.88	High
Hybrid Model (ANN + GA)	93	2.5	0.95	Very High

TABLE IV: PREDICTED VS ACTUAL CBR VALUES

Sample No.	Actual CBR (%)	Predicted CBR (%)	Error (%)
1	5.2	5.5	5.7
2	6.8	6.4	5.9
3	7.5	7.8	4.0
4	8.1	7.9	2.5
5	9.0	9.3	3.3

TABLE V: SUMMARY OF FINDINGS

Aspect	Observation
Best Performing Model	Hybrid ANN + Genetic Algorithm
Key Influencing Parameter	Moisture Content & Dry Density
Error Reduction	Up to 60% compared to traditional methods
Efficiency Improvement	Significant reduction in testing time
Practical Applicability	Highly suitable for highway subgrade design

IV. RESULTS AND ANALYSIS

The success of the research project is well exemplified by the findings that the next-generation computational processes will be effective in estimating the parameters of soil strength as associated with highway subgrades. The machine learning models, especially Artificial Neural Networks (ANN), support vector Machine (SVM), and hybrid system with the use of Genetic Algorithms (GA) performed better than conventional empirical techniques.

The comparison shows that the traditional methods like linear regression can give medium accuracy as they fail to reflect the complicated nonlinear mechanism between soil parameters. On the contrary, ANN-based models can be learned using the input variables of moisture contents, dry density and plasticity index with much higher accuracy in prediction.

The hybrid models considered, and minimal Root Mean This is because genetic algorithms are optimally applicable and therefore, it increases the learning capability of a neural network. Also, the anticipated values of California Bearing Ratio (CBR) were much similar to the lab values with slight variations. This proves that computational models are credible when it comes to estimating the properties of the soil without necessarily having widespread laboratory testing. These error margins decline and portray strong capabilities of the techniques in managing various soil environments.

It is also indicated in the study that the most influential parameters in predicting the strength of the soil are the moisture content and the dry density. The fact that computational models are effective in dealing with large sets of data and locating such key variables further plays in its favor by rendering them very useful in real life situations.

In sum, it can be concluded that the next-generation computational techniques can not only enhance the accuracy of the predictions but also cut the time, cost, and the dependence on the field testing and, therefore, are very useful in the modern highway-engineering projects.

V. CONCLUSION

This paper draws the conclusion that the next-generation computational schemes provide a very viable and dependable method of analyzing the soil strength in highway subgrades. Combining machine learning algorithms, specifically Artificial Neural Networks and hybrid models, can provide a considerably high level of accuracy when predicting such important parameters of soil. As compared to the conventional soil testing techniques, the computational techniques are quicker, cheaper, and well-suited to handle nonnew Smirnoff and difficult to measure relationships among soil characteristics. The results validate that hybrid models and specifically neural networks with optimization methods and algorithms such as genetic algorithms give the highest results in terms of accuracy and reliability.

In spite of these benefits, computational models rely on the quality of available high-quality and representative datasets in a large part. Consequently, one has to conduct right data collection, preprocessing, and validation in order to attain good prediction. To sum it up, a better efficiency and sustainability of highway design and construction can be achieved significantly with the introduction of advanced computational techniques. The next round of studies should be based on the reflection of deep learning techniques and increasing the data set size in order to improve the model results and its practical application in geotechnical engineering even more

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