IMPACT ASSESSMENT OF SOIL AND DIRECT SHEAR TEST PARAMETERS ON THE SHEAR STRENGTH OF SAND USING ARTIFICIAL INTELLIGENCE

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ABSTRACT

Shear strength is a crucial engineering property of soil, representing its ability to withstand shear stress without failure under specific normal stress conditions. However, shear strength value determined in the laboratory is subject to various influencing factors. Parameters such as soil particle gradation, relative density, and rate of shear deformation play significant roles in the test outcomes. As conducting direct shear tests in the laboratory is laborious and time consuming, Machine Learning (ML) technique namely, Random Forest Regression (RFR) is implemented to predict the shear strength of soil. Model Performance was evaluated on the basis of Coefficient of determination, Mean square error, Root mean square error and Mean square log error. The RFR yields a coefficient of determination of 0.9879 which shows the strong efficiency of RFR for solving regression problems. Additionally, sensitivity analysis was conducted to quantify the importance of each influencing factors on the Shear strength of sand and the results highlights that coefficient of curvature is the most influencing factor of angle of shearing resistance followed by the rate of shear deformation, coefficient of uniformity and relative density. Furthermore, a comparative study was carried out which shows the relationship between experimental results and sensitivity analysis.

Keywords: *Shear strength, direct shear test, relative density, machine learning, random forest regression*

1. INTRODUCTION

The shear strength of soil represents its ability to withstand shear stresses. If the shear stress at any point within the soil mass surpasses the soil's shear strength, it leads to shear failure in the soil. Consequently, shear strength is a crucial engineering property that maintains the soil stability under various loads generating shear stresses. It plays a pivotal role in the stability of slopes, soil retaining structures, and the foundation bearing capacity. The mechanism behind soil shear resistance is attributed to frictional strength and/or cohesive strength. Frictional strength considers interlocking and friction between soil particles, while cohesive strength involves chemical bonding. For granular soil like sand, shear strength is primarily due to frictional strength, whereas for fine-grained soil like clay, it results from cohesive strength. Commonly used tests like the direct shear test and triaxial tests are employed to determine soil shear strength. The direct shear apparatus is convenient for assessing the shear strength of dry cohesionless soil. However, various test parameters, such as soil gradation, relative density, and shear deformation rate, can influence the results. Understanding the impact of these parameters is crucial for adopting an appropriate testing methodology to report reliable shear strength values. Given the laborious and time-consuming nature of the direct shear test, an alternative modeling technique, Random Forest Regression (RFR), can be utilized to predict its results. In this research, soil behavior was initially assessed through laboratory tests. Subsequently, a Machine Learning (ML) model was developed using the same data to predict direct shear test results. The study also conducted sensitivity analysis to quantify the influence of test and soil parameters on the angle of shearing resistance.

2. SCOPE AND PRESENT STUDY

Considerable research has been done on the effect of different parameters viz. gradation, relative density, state of sand as dry or saturated, and rate of shear deformation on angle of shearing resistance of sand. Shear strength of sand is influenced by various parameters like relative density, presence of water, particle size distribution, strength of soil particles, shape and size of soil particles and degree of saturation of the test specimen (Yu et al., 2006). Influence of different laboratory assistants, specimen sizes and displacement rates on the shear strength of highly heterogeneous till are tested (Thermann et al., 2006). Different rate of shear deformation result in different values of shear strength. The shear strength values obtained from low rate of shear deformation are higher than the values obtained with high rate of shear deformation (Nguyen, 2009). Uniformly graded sand possesses less shear strength than well graded or poorly graded sand. Shear strength of sand increases with increases in water content (Badhon & Islam, 2017). Shear strength of sand and quarry dust increases with the increase in dry density of the sample particle size (Kakati & Chetia, 2020).

3. MATERIALS USED

The soil used for the study is collected from Champa river basin at Kokrajhar district of Assam, India. Soil classification test reveals the type of soil as poorly graded sand (SP). Particle size distribution graph for the soil is shown in figure 1. Through sieves of different sizes, this soil is further segregated to obtain soils of different gradations as Well Graded (WG), Uniformly Graded (UG) and Gap Graded (GG). Particle size distribution graphs for WG, UG and GG soil are shown in figure 2-4. Vibratory table tests are conducted on these types of sand to determine their minimum and maximum dry density, which are tabulated in table 1.

Table 1: Properties of different sand

Sand Type	D_{60} (mm)	D_{30} (mm)	D_{10} (mm)	C_U	C_C	γ_{dMax} g/cc	γ_{dMin} g/cc
WG	1.9	1	0.31	6.33	1.69	1.72	1.45
PG	1.4	0.9	0.7	2	0.83	1.65	1.44
GG	1.1	1	0.21	5.23	4.33	1.60	1.42
UG	2.1	2.1	2.1	1	1	1.56	1.41

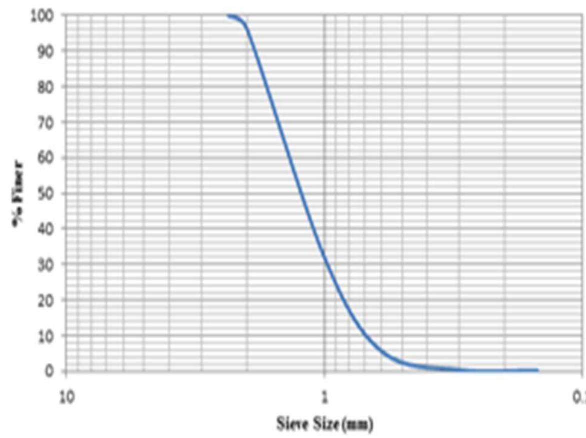

Figure 1: Particle size distribution graph for Poorly Graded sand (PG)

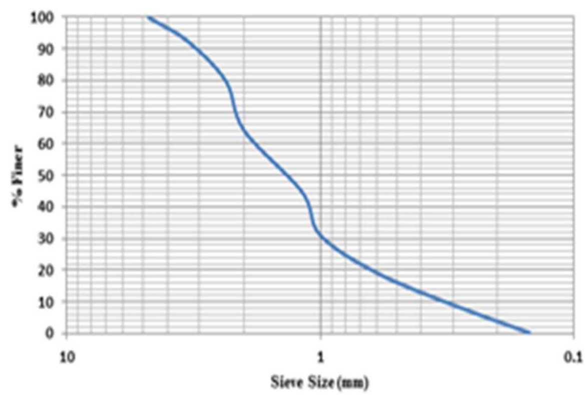

Figure 2: Particle size distribution graph for Well Graded sand (WG)

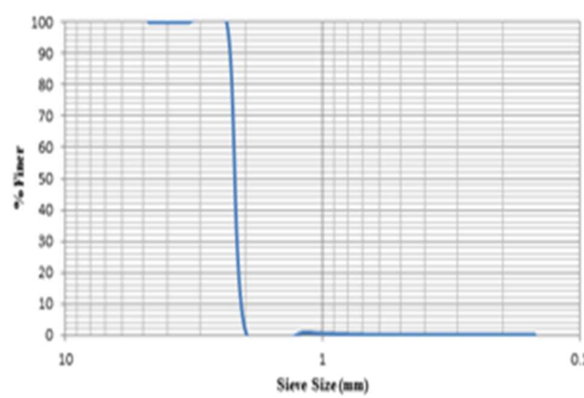

Figure 3: Particle size distribution graph for Uniformly Graded sand (UG)

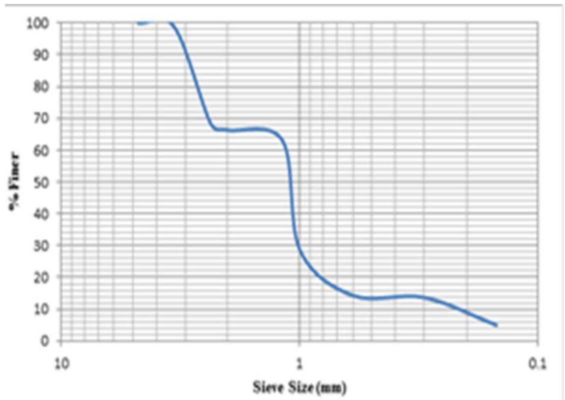

Figure 4: Particle size distribution graph for Gap Graded sand (GG)

4. EXPERIMENTAL METHODOLOGY

The present research work employs large scale direct shear apparatus to study the effect of various test and soil parameters on shear strength of cohesionless soil. The apparatus used is shown in figure 5. It consists of a shear box of size 300 mm x 300 mm x 200mm. A proving ring to measure shear load and dial gauge to measure horizontal displacement.

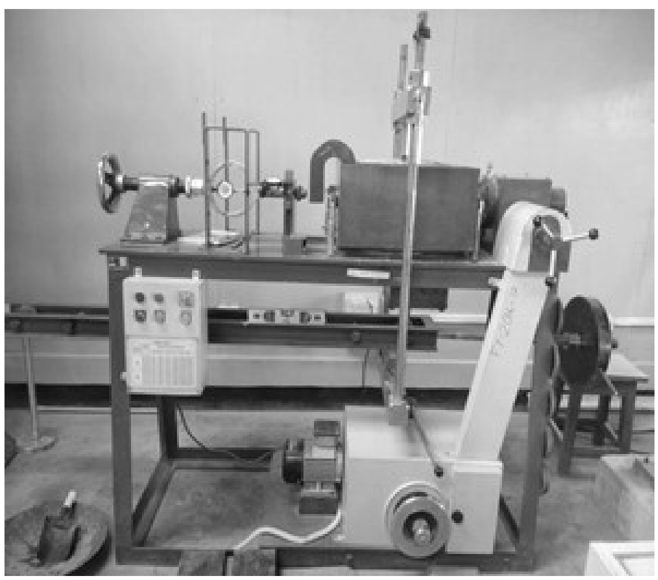

Figure 5: Direct shear apparatus

Methodology of testing involves preparing in the shear box different gradation of sand samples with different relative densities and testing them under different rates of shear deformation. For this, each gradation of sand samples viz. WG, PG, UG and GG are prepared with different relative density viz. 40%, 55%, 70% and 85% to represent very loose, loose, dense and very dense sand samples respectively. Each gradation of sand sample at every relative density is tested for different rates of shear deformation viz. 10.16, 5.678 and 1.01 mm/min. To obtain shear strength values for a particular type of gradation of sand sample at particular relative density and rate of shear deformation, three different normal stresses, 50kN/m^2, 100kN/m^2 and 150kN/m^2 are used. For every normal stress, graph is drawn between horizontal displacements vs. shear stresses to obtain maximum value of shear stress at failure. For a particular soil sample sheared at a particular rate of shear deformation, a graph is drawn between normal stresses and maximum shear stresses to obtain shear strength parameters.

Graph for one sample sheared under a particular rate of shear deformation are compared with others for analysis.

5. EXPERIMENTAL RESULTS

To understand the influence of different test and soil parameters on shear strength of soil, graphs are plotted as shown in the figure 6 - 9. Graphs are plotted between angle of shearing resistance and rate of shear deformation for different gradations of soil maintained at different relative densities (D_r). For all the cases well graded soil shows highest angle of shearing resistance followed by poorly graded, gap graded and uniformly graded. Well graded soil has particles of all sizes hence voids between larger particles will be filled with smaller size particles. As a result, well graded soil has more density and better grip between particles against shear deformation. In case of poorly graded soil, a sufficient number of smaller size particles may not be available to fill the voids between large size particles. This may result in lesser density and lesser grip between soil particles resulting in lesser angle of shearing resistance compared to WG soil. In case of Gap graded soil, particles of a certain size will be absent. Hence, certain voids will be left unfilled. GG soil shows less angle of shearing resistance compared to WG soil. Depending on the extent of absence of different particle sizes, It may show lesser angle of shearing resistance than PG soil. Uniformly graded soil has all particles of the same size. Hence, it has highest voids and least density as no small size soil particles will be available to fill the voids between large particles. Therefore, uniformly graded soil offers least resistance to shear deformation. Low rate of shear deformation gives sufficient time for soil particles to rearrange themselves for better interlocking during shearing phase hence yielding better angle of shearing resistance. Higher relative density establishes better contact between soil particles.

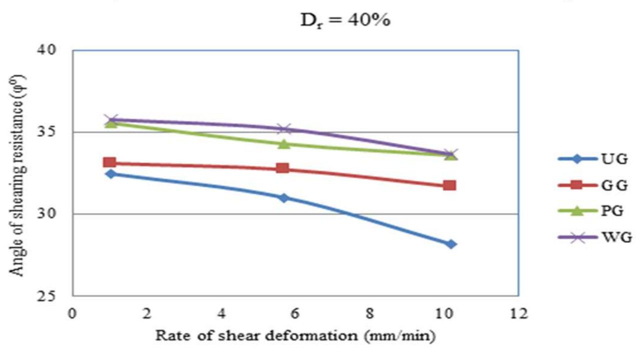

Figure 6: Influence of rate of shear deformation on angle of shearing resistance for soil at 40% relative density

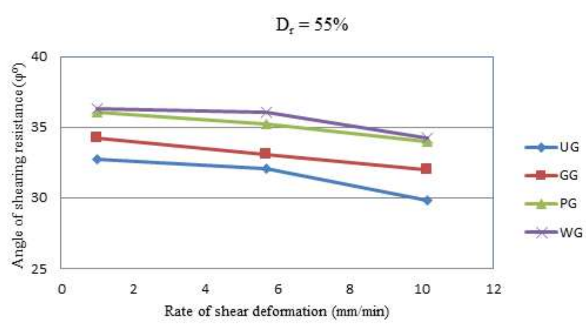

Figure 7: Influence of rate of shear deformation on angle of shearing resistance for soil at 55% relative density

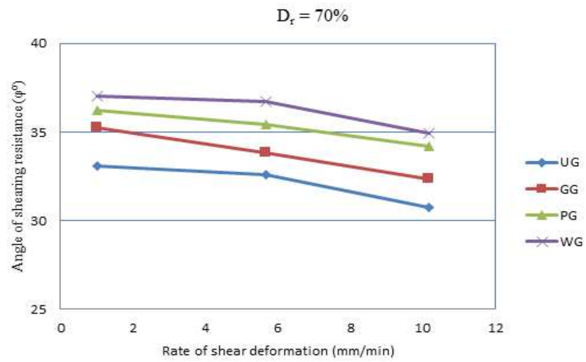

Figure 8: Influence of rate of shear deformation on angle of shearing resistance for soil at 70% relative density

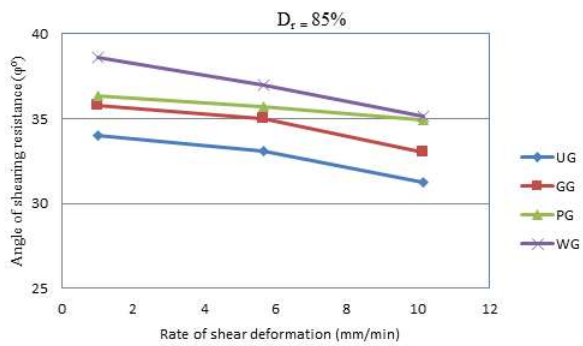

Figure 9: Influence of rate of shear deformation on angle of shearing resistance for soil at 85% relative density

6. RANDOM FOREST REGRESSION

In this approach to modeling, decision trees are utilized in both classification and regression scenarios. When addressing regression problems, the process starts at the tree's root and involves successive splits based on variable outcomes until a leaf node is reached, delivering the conclusion (Random Forest Regression, 2022). A type of ensemble regression analysis is random forest (RF) which is developed by Ho, T. K. (Ho, 1995, 1998) and it is based on a hybrid random subspace technique. Furthermore, highly reliable models are developed by Breiman, L. (Breiman, 1996) based on bootstrap technique. This method operates as a supervised machine learning algorithm. The basic structure of RF is demonstrated in figure 11, which is used to predict the angle of shearing resistance of soil in this study.

7. MODEL FORMULATION

In the present study, a dataset which has been developed by the laboratory test is used for formulating the RFR model. The statistical representations of input parameters are shown in table 2. The table 2 reveals that C_U, C_C, relative density (D_r) and rate of shear deformation (SD) has been used as input parameters in order to forecast the angle of shearing resistance. In order to develop the model, python programming language has been utilized in google colab.

Methodology for model formulation is demonstrated in figure 12. It shows that the required dataset is obtained from lab experiments. The dataset obtained is normalized and then divided into two parts for training and testing. The model is trained using training data and checked for its accuracy using testing data.

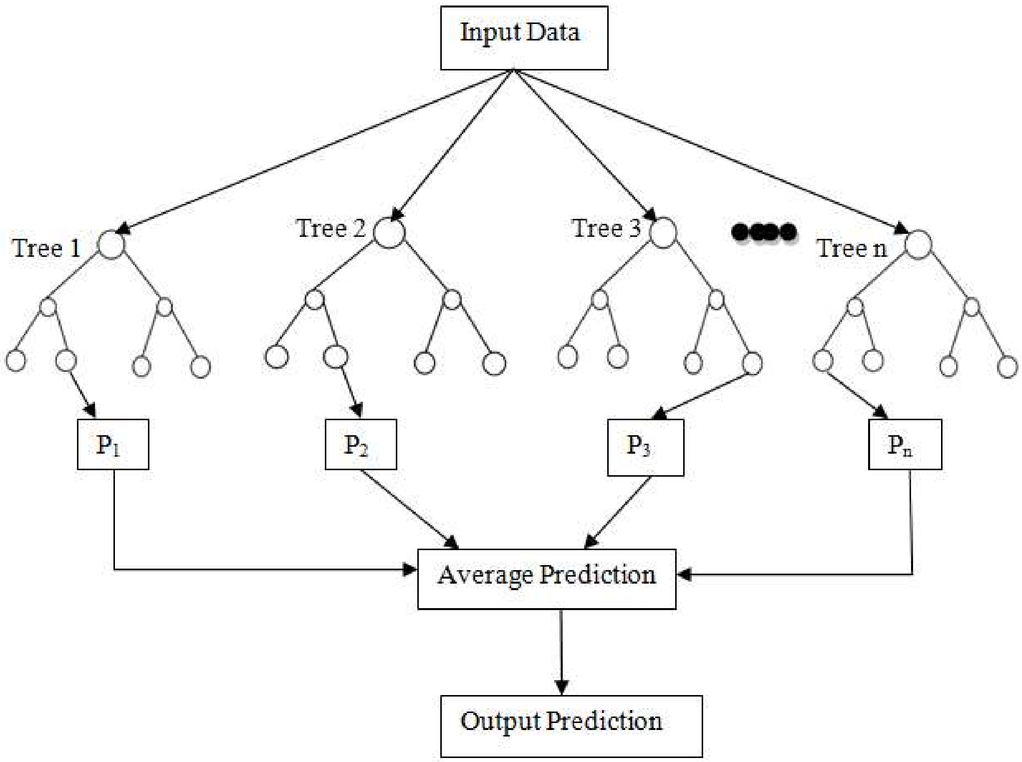

Figure 11: RF structure

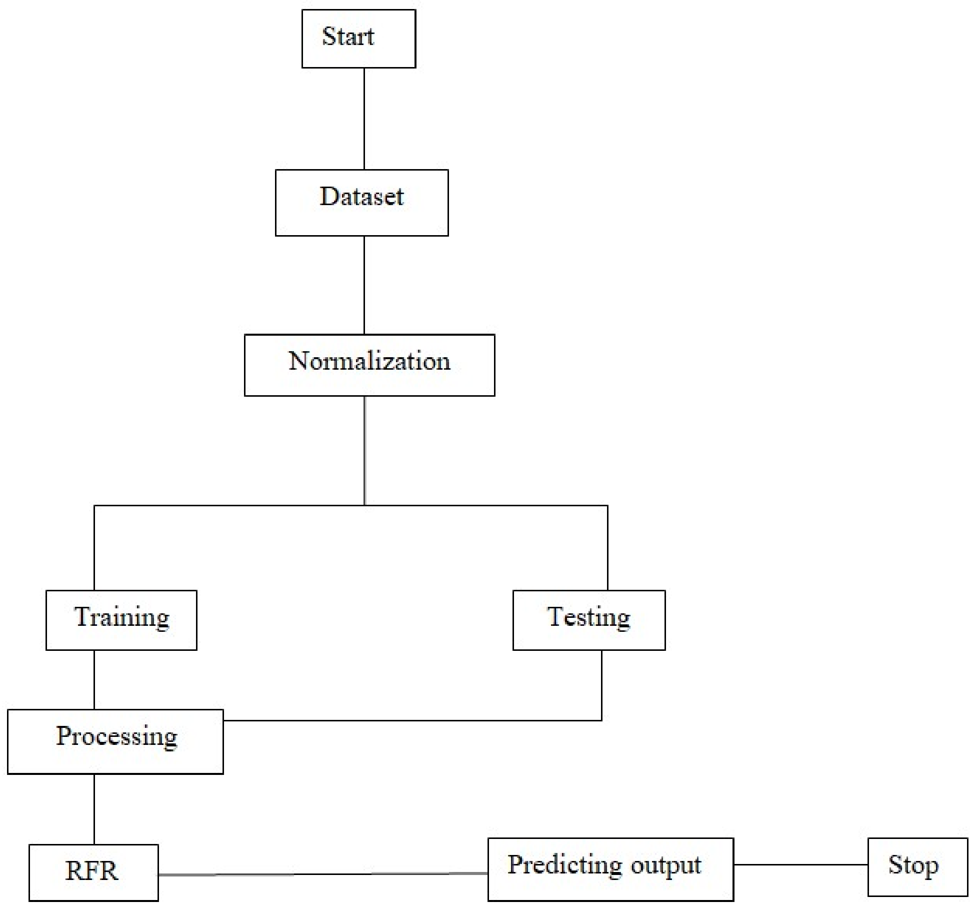

Figure 12: Model formulation steps

Table 2: Statistical representation of input data

	C_U	C_C	D_r	SD
count	48	48	48	48
mean	3.3475	2.1675	62.5	5.616
std	2.490203	1.291736	16.94798	3.775262
min	0.83	1	40	1.01
25%	0.9575	1.4875	51.25	1.01
50%	3.115	1.67	62.5	5.678
75%	5.505	2.35	73.75	10.16
max	6.33	4.33	85	10.16

8. RESULTS BASED ON RFR

The assessment of model performance included the consideration of coefficient of determination (R^2), Mean Square Error (MSE), Root Mean Square Error (RMSE), and Mean Square Log Error (MSLE). Table 3 presents the model performance parameters, indicating that the model is effectively trained, as evidenced by an R^2 value of 0.9879. The corresponding MSE, RMSE, and MSLE values are 0.0503, 0.2243, and 4.6422, respectively. The figure 13 shows the actual values and predicted values.

Table 3: Model performance parameter

R^2	MSE	RMSE	MSLE
0.9879	0.0503	0.2243	4.6422

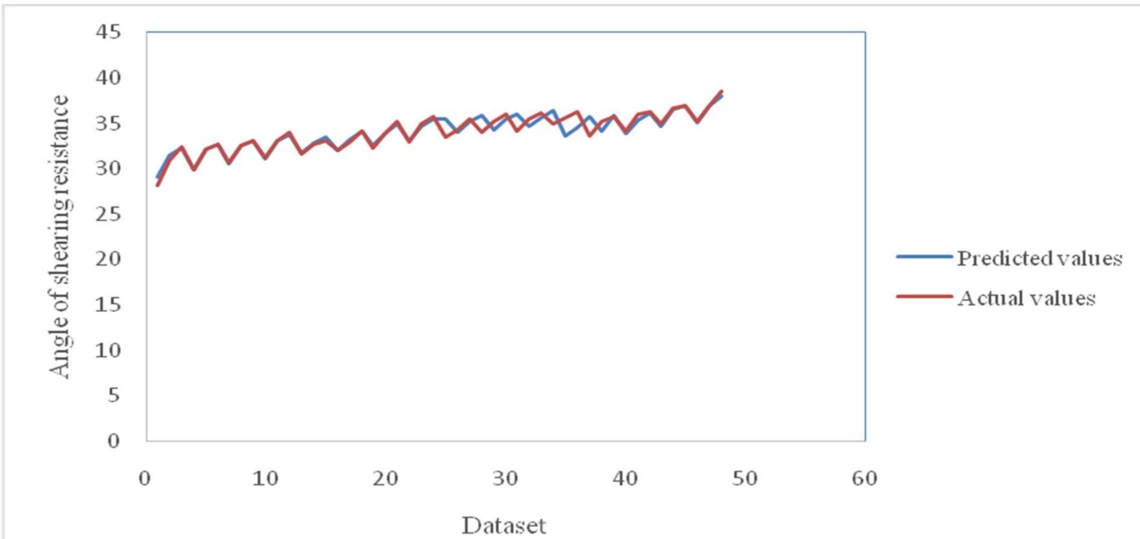

Figure 13: Actual values vs. Predicted values

9. SENSITIVITY ANALYSIS

Sensitivity analysis has been conducted using RFR for calculating the feature importance, which demonstrates which factor influences the angle of shearing resistance the most. Results of sensitivity analysis are presented in figure 14. Results show that the C_C influences the angle of shear resistance the most with a percentage of 47.72% followed by rate of shear deformation, C_U and Relative density with an influence of 25.88%, 13.63% and 12.78% respectively.

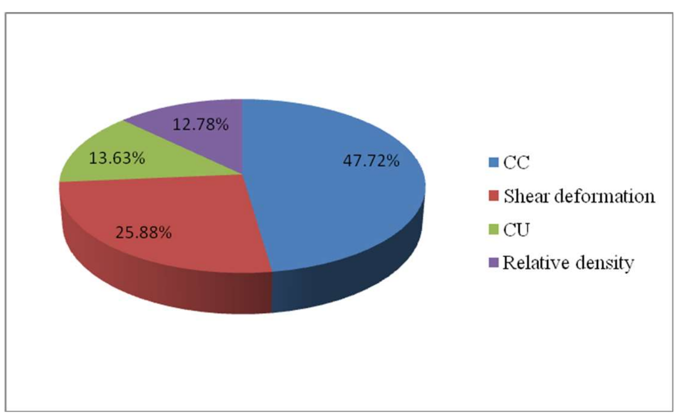

Figure 14: Sensitivity Analysis

10. COMPARATIVE STUDY

The experimental results introduce key concepts about the influence of relative density and shear deformation, and soil gradation on shear strength. Sensitivity analysis (SA) provides the numerical validation of the qualitative relationships. Experimental results show that an increase in relative density enhances shear strength, and the SA confirms this by assigning a specific percentage of importance to relative density in influencing the angle of shearing resistance.

In the present study, experimental results discuss the influence of shear deformation on shear strength, and the result of SA quantifies this influence by attributing a percentage of importance to the rate of shear deformation. Additionally, the experimental result highlights the impact of soil gradation on shear strength, and SA aligns with this by revealing the significance of factors like C_c, C_u, which are closely related to the gradation of soil.

11. CONCLUSION

The conclusion from the laboratory experiments of the present study provides valuable insights into the factors influencing the shear strength of soil. One of the key findings is that soil samples containing particles of all sizes demonstrate superior strength against shear failure. This observation underscores the importance of a well-graded composition in enhancing shear strength of soil. The study also highlights the relationship between the non-availability of soil particles of specific sizes and the corresponding decrease in shear strength. Consequently, a well-graded soil emerges as having the highest shear strength, followed by poorly graded, gap graded, and uniformly graded soils in descending order. Later on, the data obtained from the laboratory experiment has been used in order to predict the direct shear test result with the help of RFR. The results highlight that RFR is a very strong tool, which can be used in the field of geotechnical engineering. In addition, it is a good ML approach for predicting continuous values, which is confirmed by the results shown in figure 13. Additionally, SA shows that C_c influences the angle of shearing resistance the most compared to other parameters. Furthermore, a comparative study was carried out which shows the relationship between experimental results and SA results.

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