

# Reliability Modeling of Vertical Spatial Soil Variability

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**Abstract**—The study performed a reliability model of vertical spatial soil variability a location, at Port Harcourt, Rivers state, in the Niger Delta Region of Nigeria This study relied on laboratory test data from field investigation report of the study area. The model involves the use of Least Square method in simulating and analyzing data collated from the study area using Python and Microsoft excel tool. Cohesion (Cu) and Angle of internal friction( $\phi$ ), were a function of depth (d), liquid limit (LL), plastic limit (PL) and unit weight ( $\gamma$ ) from field test results, which were used to stimulate and predict new Cu and  $\phi$  values at arbitrary depth in the model. The Independent soil parameters were alternated in the model for different conditions to ascertain their varying effects on the predicted Cu and  $\phi$  values. The model established reliable prediction of soil parameters for design purpose using existing field data of vertical spatial variable soil parameters form the study area, The model was further validated as the correlation coefficient ( $r^2$ ) recorded  $r^2=0.6846$  and  $r^2=0.6526$  for predicted Cu and  $\phi$  values respectively. Predicted Cu and  $\phi$  values were increasing and decreasing with respect to changes in depth (d), LL, PL and  $\gamma$  of the soil. Subsurface of very soft clay from the ground level to various depths between 3.0m and 5.25m thick overlying medium dense sand to the final depth of the investigation at the estate site in Port Harcourt. It is therefore possible to predict reliable soil parameters of vertical spatial soils for depths not investigated for design purpose using available field data of known depths from the study area

**Keywords**—Reliability Modelling, Spatial Soil Variability Cohesion, Angle of Internal friction, Index properties and depth.

## I. INTRODUCTION

In recent advancements emphases have been made in integrating statistical and probabilistic modeling techniques to understand vertical soil variability more accurately. Studies by Baziar *et al* [1] and others reveal that adopting stochastic processes aids in more robust predictions of soil behavior under various loading conditions. These methods typically involve random field theory and reliability-based design approaches, reflecting a nuanced understanding of spatial variability influences (Huang *et al.*,[2].

Furthermore, the adoption of machine learning tools in geotechnical reliability analysis has seen an upsurge, reflecting a trend towards more sophisticated data analysis capabilities.

This integration allows for more refined modeling of soil characteristics, enabling geotechnical engineers to derive insights from large datasets efficiently (Zhang & Zhang,[3]. While promising, these techniques also highlight a significant challenge: the need for high-quality, extensive geotechnical data, which is often limited.

An essential discourse within this domain involves the balance between model complexity and practical applicability. According to Liu and Wang [4], the overly complex models may offer precision but at the expense of user-friendliness and interpretability, which can hinder practical implementation.

Despite these advancements, gaps remain. There is a substantial need for standardized data collection methods and the establishment of more universally applicable models. Additionally, ongoing debates focus on improving model validation techniques and the integration of interdisciplinary approaches to enrich soil variability understanding.

Reliability Modeling has become a task of technical importance across various fields and disciplines in engineering, due to the high level of risk factors and uncertainties regarding the safety of engineering system designs are a significant concern. A reliability model offers a comprehensive understanding of the functional interdependencies within a product, facilitating trade-offs among different design alternatives and highlighting opportunities for design enhancements. Geotechnical reliability can be broadly characterized as a systematic approach that improves decision-making throughout various stages of a project's life cycle, including design, construction, operation, maintenance, retrofitting, and decommissioning or reuse. This methodology leverages a more sophisticated data characterization through the use of probabilistic models. Variability plays a significant role in introducing uncertainty within geotechnical engineering analyses

Geotechnical site investigations are a critical aspect In the field of civil engineering and construction ventures particularly when determining the suitability of proposed locations for new facilities. These investigations primarily focus on assessing the soil and groundwater conditions which can significantly impact the design and overall stability of any structures to be built.



A thorough understanding of soil conditions can prevent costly failures, hazardous conditions, and safety risks associated with civil engineering projects. The adoption of representative single values for the soil properties is typical of the deterministic approach in the geotechnical design of structures in which the unpredictability linked to the spatial heterogeneity of soil parameters is accounted for by incorporating a safety factor (FS) value that reflects the engineer's experience, perception of risk and the level of confidence in the value of ten derived geotechnical parameter (Elkateb *et al.*, 2003[5]).

Soils are naturally existing materials generated by weathering, as their physical properties differ from one location to another due to physical and chemical changes that occur during formation, as well as their stress history. The consideration of the variability observed in soils, even among those that are homogeneous, justifies the need for the probabilistic modelling of the soil profiles as captured by Vanmarcke[6]. The approach recognizes the spatial variability of soils horizontally and vertically moving from one point to another. Uncertainty is a significant factor in various dimensions of geotechnical engineering, especially when it comes to the assessment of soil properties. Reliability of a geotechnical system is the ability of the system to serve its intended purpose without risk and uncertainties during the life cycle of that system. The enormous advantages of reliability modeling developed on reliability based design (RBD) methods against deterministic methods in geotechnical engineering system has given it technical superiority over the latter [7] The distinguishing qualities of the geotechnical engineer is that the engineer has to work with natural materials in an environment that are largely outside his control, and these physical ground conditions which are of his interest are very complex and keeps changing at different time and scales with respect to depths and prevailing environmental conditions.

Variability occurs in geotechnical design parameters, constitutively in these designs principal to reliability modeling is the assessment of geotechnical parameters and the subsequent probabilistic analysis of these factors play a crucial role in engineering projects. This process involves systematically evaluating soil characteristics and their variabilities to enhance site performance predictions. Some key components and primary statistics needed for computation in this research are the mean, variance, standard deviation, scale of fluctuation and coefficient of variation. The performance of geotechnical structures is heavily influenced by the local extremes of subsurface properties. Therefore, it is essential to adopt a probabilistic approach in characterizing soil profiles.

This method enables a systematic quantification of geotechnical information related to the subsurface conditions at a specific site. By employing probabilistic characterization, engineers are able to predict the performance of geotechnical structures, assess the likelihood of failure, and rigorously evaluate and compare different site investigation and testing programmes, thereby determining their effectiveness.

## II. SIGNIFICANCE OF STUDY

The research is significant and will contribute to the following areas:

1. Provide an understanding of the profile stratigraphy of soils and determine the nature of soil property spatial (vertically) variability given the stratigraphy of the area.
2. Provide an adequate tool for engineers to carry out preliminary designs for foundations of geotechnical structures within the study area using values of the soil property estimated from the relevant models without exploring certain depths in geotechnical field investigations.
3. The research will be useful for reference purposes to the geotechnical engineers and other professionals.

## III. AIM OF STUDY

The uncertainties associated with risks in geotechnical engineering has been attributed to spatial variability in soil and to some extent the inaccurate deterministic analysis of geotechnical systems, Hence the aim of this study is to carry out reliability analysis and develop a model of vertical spatial variable soils for prediction of engineering properties at locations and depths not included in geotechnical investigation.

## IV. OBJECTIVE OF STUDY

This research is primarily focused on the collation of data and the analysis of these data to develop parameters and statistics required for reliability modeling of vertical spatial variable soils, and to demonstrate the application of these parameters and statistics in the analysis and design of geotechnical engineering systems. Hence the main objectives of this research are as follows:

1. Evaluate the effects of vertical spatial soil variability on geotechnical reliability.
2. Characterize cohesive and non cohesive soils base on vertical spatial variability in study areas for reliability analysis.

3. To develop a reliable model/framework to determine vertical spatial variability of soil and geotechnical parameters using reliability based design (RBD) techniques.
4. Assess the impact of spatial variability on the performance of geotechnical structures.

#### V. RESEARCH METHODOLOGY

The research adopted the sourcing and handling of data from the study area. It also highlights the organization of the data and various statistical analysis performed to generate the geotechnical parameters used in the study. This research involves the use of Microsoft Excel office tool, Python software tool and the data sets generated from the study area, the data sets which are geotechnical soil parameters of laboratory test investigation of 16 borehole points of the study area. The Laboratory test investigations include:

1. Natural Moisture test
2. Atterberg limits test( Liquid Limit, Plastic Limit)
3. Triaxial test
4. Standard Penetration test
5. Direct shear box test.

The Study area is located within the Niger Delta region, as data from investigations were generated from a Gas plant and a proposed residential area located in Port Harcourt, Rivers Stat. The equipments used in sampling/collection of soil samples from the study area is the SPT manual drilling rig and the Light hand operated auger apparatus.

#### A. Data Acquisition

The data for the study are those from geotechnical site investigation report with detailed information relating to the nature of the subsurface sediments, ground water conditions and geotechnical soil parameters such as cohesion, angle of internal friction, index properties and unit weight of soil used for the design of geotechnical structures in the study area.

Data sets were collated a total number of 16 boreholes points. The geotechnical parameters from the site were carefully analyzed together for a proper simulation of the model and the outcome of reliable results.

#### B.. Methods

The method used in this research focused on the application of Least square method in the simulation of the geotechnical data sets from laboratory test investigation of the study area to develop a reliable model for prediction of geotechnical parameters for the purpose of design. The research model is a function of cohesion ( $C_u$ ) and angle of internal friction ( $\phi$ ) which are dependent on depth ( $d$ ), unit weight of soil ( $\gamma$ ), liquid limit (LL), plastic limit (PL). The use of Python computer aided software and Microsoft excel was of huge significance in this research.

Mathematical models were developed utilizing the least squares approach, implemented through Python scripting, to predict both the cohesion and the angle of internal friction of soil at any arbitrary depth. The parameters of cohesion and the angle of internal friction are expressed as functions of soil depth( $D$ ), along with liquid limit (LL), plastic limit (PL), and the effective unit weight of the soil ( $\gamma'$ ).  $a, b, c, d$  and  $e$  are constants.

Equation (1) presents the model for the prediction of Cohesion.

$$1 + C_u = a(1 + D)^b(1 + W)^c(1 + P)^d(\gamma')^e \quad (1)$$

Linearizing Equation (1) yields Equation (2)

$$\ln(1 + C_u) = \ln a + b \ln(1 + D) + c \ln(1 + W) + d \ln(1 + P) + e \ln(\gamma') \quad (2)$$

The solution matrix for Cohesion is given in Equation (3)

$$\left\{ \begin{array}{l} \sum_{i=1}^n \ln(1 + C_u) \\ \sum_{i=1}^n \ln(1 + C_u) \ln(1 + D) \\ \sum_{i=1}^n \ln(1 + C_u) \ln(1 + W) \\ \sum_{i=1}^n \ln(1 + C_u) \ln(1 + P) \\ \sum_{i=1}^n \ln(1 + C_u) \ln(\gamma') \end{array} \right\} =$$

$$\left[ \begin{array}{ccccc} n & \sum_{i=1}^n \ln(1 + D) & \sum_{i=1}^n \ln(1 + W) & \sum_{i=1}^n \ln(1 + P) & \sum_{i=1}^n \ln(\gamma') \\ \sum_{i=1}^n \ln(1 + D) & \sum_{i=1}^n [\ln(1 + D)]^2 & \sum_{i=1}^n \ln(1 + D) \ln(1 + W) & \sum_{i=1}^n \ln(1 + D) \ln(1 + P) & \sum_{i=1}^n \ln(1 + D) \ln(\gamma') \\ \sum_{i=1}^n \ln(1 + W) & \sum_{i=1}^n \ln(1 + W) \ln(1 + D) & \sum_{i=1}^n [\ln(1 + W)]^2 & \sum_{i=1}^n \ln(1 + W) \ln(1 + P) & \sum_{i=1}^n \ln(1 + W) \ln(\gamma') \\ \sum_{i=1}^n \ln(1 + P) & \sum_{i=1}^n \ln(1 + P) \ln(1 + D) & \sum_{i=1}^n \ln(1 + P) \ln(1 + W) & \sum_{i=1}^n [\ln(1 + P)]^2 & \sum_{i=1}^n \ln(1 + P) \ln(\gamma') \\ \sum_{i=1}^n \ln(\gamma') & \sum_{i=1}^n \ln(\gamma') \ln(1 + D) & \sum_{i=1}^n \ln(\gamma') \ln(1 + W) & \sum_{i=1}^n \ln(\gamma') \ln(1 + P) & \sum_{i=1}^n [\ln(\gamma')]^2 \end{array} \right] \begin{Bmatrix} lna \\ b \\ c \\ d \\ e \end{Bmatrix} \quad (3)$$

Equation (4) presents the model for the prediction of Angle of internal friction.

$$\tan(1 + \phi) = a(1 + D)^b(1 + W)^c(1 + P)^d(\gamma')^e \quad (4)$$

Linearizing Equation (4) yields Equation (5)

$$\ln[\tan(1 + \phi)] = lna + b \ln(1 + D) + c \ln(1 + W) + d \ln(1 + P) + e \ln(\gamma') \quad (5)$$

The solution matrix for angle of Internal friction is given in Equation (6)

$$\left\{ \begin{array}{l} \sum_{i=1}^n \ln[\tan(1 + \phi)] \\ \sum_{i=1}^n \ln[\tan(1 + \phi)] \ln(1 + D) \\ \sum_{i=1}^n \ln[\tan(1 + \phi)] \ln(1 + W) \\ \sum_{i=1}^n \ln[\tan(1 + \phi)] \ln(1 + P) \\ \sum_{i=1}^n \ln[\tan(1 + \phi)] \ln(\gamma') \end{array} \right\} =$$

$$\left[ \begin{array}{ccccc} n & \sum_{i=1}^n \ln(1 + D) & \sum_{i=1}^n \ln(1 + W) & \sum_{i=1}^n \ln(1 + P) & \sum_{i=1}^n \ln(\gamma') \\ \sum_{i=1}^n \ln(1 + D) & \sum_{i=1}^n [\ln(1 + D)]^2 & \sum_{i=1}^n \ln(1 + D) \ln(1 + W) & \sum_{i=1}^n \ln(1 + D) \ln(1 + P) & \sum_{i=1}^n \ln(1 + D) \ln(\gamma') \\ \sum_{i=1}^n \ln(1 + W) & \sum_{i=1}^n \ln(1 + W) \ln(1 + D) & \sum_{i=1}^n [\ln(1 + W)]^2 & \sum_{i=1}^n \ln(1 + W) \ln(1 + P) & \sum_{i=1}^n \ln(1 + W) \ln(\gamma') \\ \sum_{i=1}^n \ln(1 + P) & \sum_{i=1}^n \ln(1 + P) \ln(1 + D) & \sum_{i=1}^n \ln(1 + P) \ln(1 + W) & \sum_{i=1}^n [\ln(1 + P)]^2 & \sum_{i=1}^n \ln(1 + P) \ln(\gamma') \\ \sum_{i=1}^n \ln(\gamma') & \sum_{i=1}^n \ln(\gamma') \ln(1 + D) & \sum_{i=1}^n \ln(\gamma') \ln(1 + W) & \sum_{i=1}^n \ln(\gamma') \ln(1 + P) & \sum_{i=1}^n [\ln(\gamma')]^2 \end{array} \right] \begin{Bmatrix} lna \\ b \\ c \\ d \\ e \end{Bmatrix} \quad (6)$$

### VI. RESULT AND DISCUSSION

The experimental data obtained from laboratory site investigations in the study areas were compiled and referred to as "Experimental Results." These results were subsequently employed in the model to generate simulated outcomes at varying depths, termed "Predicted Results."

Both sets of data are presented in Tables 1 and 2. The predicted values of cohesion (Cu) and angle of internal friction (φ) detailed in Tables 1 to 2 are accompanied by the corresponding independent soil parameters derived from the modeling program developed using python encrypting.

**Table 1**  
**Experimental Results from Estate, Resident at P/H City, Estate Geotechnical Field Investigation**

Borehole Nos.	Depth		Unit Weight		Atterberg limit			Strength	
	(d)	(Dry)	(Effective)	LL	PL	PI	Cohesion	Phi	
	m	kN/m <sup>3</sup>	kN/m <sup>3</sup>	%	%	%	kN/m <sup>2</sup>	ϕ°	
1	3.00	15.5	9.2	0	0	0	0	28	
	3.75	-	8.8	63	33	30	0	0	
	4.50	6.2	3.8	69	31	38	7	0	
	6.00	-	8.4	74	42	32	0	0	
	8.25	17.0	10	0	0	0	0	31	
	12.00	16.8	9.6	0	0	0	0	29	
	21.00	16.8	9.8	0	0	0	0	30	
	24.00	14.1	8.8	52	27	25	51	0	
	25.50	-	7.7	41	22	19	0	0	
	27.00	17.2	11	0	0	0	0	29	
2	3.00	5.5	3.5	63	29	34	9	0	
	3.75	-	7	75	45	30	0	0	
	9.00	17.6	10.6	0	0	0	0	30	
	25.50	16.8	10.2	56	28	28	60	0	
	27.00	-	7.9	66	35	31	45	0	
3	27.75	14.8	7.5	0	0	0	0	29	
	1.50	-	6.6	80	48	32	0	0	
	3.00	5.1	3	75	44	31	11	0	
	4.50	-	8.9	46	25	21	0	0	
	10.50	16.1	8.6	0	0	0	0	28	
	15.75		9.3	0	0	0	0	0	
	21.00	17.8	11.1	0	0	0	0	31	
26.25	-	10	29	16	13	0	0		



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	3.00	-	18.9	80	48	32	0	0
4	5.25	16.0	19.2	0	0	0	0	30
	18.00	17.0	20.2	0	0	0	0	30
	26.25	16.3	19.4	0	0	0	0	28
	27.00	-	19.1	55	25	30	0	0
	27.75	-	18.6	45	23	22	0	0
5	2.25	17.6	17.6	0	0	0	0	30
	3.75	19.9	19.9	57	30	27	0	0
	4.50	12.9	12.9	65	37	28	10	0
	5.25	19.5	19.5	0	0	0	0	29
	12.00	19.4	19.4	0	0	0	0	30
	24.00	19.9	19.9	0	0	0	0	30
6	1.50	20.1	20.1	45	23	22	0	0
	3.00	17.9	17.9	41	18	23	0	0
	3.75	19.8	19.8	0	0	0	0	29
	12.00	19.2	19.2	0	0	0	0	30
	21.00	18.1	18.1	0	0	0	0	31
	26.25	20.7	10.9	42	25	17	25	0
	27.75	19.4	9.6	0	0	0	0	28
7	1.50	19.3	9.5	57	30	27	0	0
	3.00	20.4	10.6	53	35	18	13	0
	3.75	19.2	9.4	0	0	0	0	29
	9.00	19	9.2	0	0	0	0	30
	15.00	17.7	7.9	0	0	0	0	0
	21.00	18.5	8.7	0	0	0	0	30
	1.50	16.3	6.5	79	48	31	0	0
	2.25	19	9.2	68	39	29	0	0



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8	3.00	19.9	10.1	0	0	0	0	33
	6.00	20.1	10.3	0	0	0	0	28
	15.00	20.1	10.3	0	0	0	0	28
	20.25	20.4	10.6	76	45	31	0	0
	21.75	20.8	11	0	0	0	0	28
	24.00	19.4	9.6	0	0	0	0	29
	1.50	15.7	5.9	58	33	25	0	0
	2.25	12.7	2.9	48	23	25	6	0
9	3.75	17.5	7.7	66	36	30	0	0
	4.50	19.4	9.6	0	0	0	0	28
	9.00	20.9	11.1	0	0	0	0	28
	22.50	20.4	10.6	0	0	0	0	29
	23.25	19.6	9.8	48	20	28	0	0
	24.00	17.7	7.9	53	32	21	29	0
	26.25	16.8	7	55	26	29	0	0

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**Table 2**  
**Predicted results of Decrease in Effective Unit Weight, Increase in Liquid Limit, Plastic Limit and Depth**

Depth d(m)	Liquid limit (%)	Plastic limit (%)	Unit Weight, $\gamma$ (kN/m <sup>3</sup> )	Predicted Cu (kN/m <sup>2</sup> )	Predicted ( $\phi^\circ$ )
0	0	0	25	10.55415	71.5422595
0.1	1	0.5	24.85	17.68541	56.6523405
0.2	2	1	24.7	23.19103	46.6632812
0.3	3	1.5	24.55	27.78438	39.698629
0.4	4	2	24.4	31.77152	34.5887715
0.5	5	2.5	24.25	35.31478	30.6745926
0.6	6	3	24.1	38.51196	27.5718059
0.7	7	3.5	23.95	41.42726	25.0445111
0.8	8	4	23.8	44.10553	22.9406327
0.9	9	4.5	23.65	46.57965	21.1578659
1	10	5	23.5	48.87459	19.624844
1.1	11	5.5	23.35	51.00992	18.2902225
1.2	12	6	23.2	53.00138	17.1160769
1.3	13	6.5	23.05	54.86182	16.0737532
1.4	14	7	22.9	56.602	15.1411735
1.5	15	7.5	22.75	58.23101	14.3010333
1.6	16	8	22.6	59.75665	13.5395632
1.7	17	8.5	22.45	61.18567	12.8456605
1.8	18	9	22.3	62.52401	12.2102651
1.9	19	9.5	22.15	63.77689	11.6259052
2	20	10	22	64.94899	11.0863592
2.1	21	10.5	21.85	66.04449	10.5864015
2.2	22	11	21.7	67.06717	10.1216081
2.3	23	11.5	21.55	68.02045	9.68820678
2.4	24	12	21.4	68.90747	9.28295947
2.5	25	12.5	21.25	69.73111	8.90306981
2.6	26	13	21.1	70.494	8.54610926
2.7	27	13.5	20.95	71.19861	8.20995772
2.8	28	14	20.8	71.8472	7.89275538
2.9	29	14.5	20.65	72.44189	7.59286345
3	30	15	20.5	72.98467	7.30883179
3.1	31	15.5	20.35	73.4774	7.03937215
3.2	32	16	20.2	73.92181	6.78333589
3.3	33	16.5	20.05	74.31957	6.53969529
3.4	34	17	19.9	74.67222	6.30752782



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3.5	35	17.5	19.75	74.98124	6.08600286
3.6	36	18	19.6	75.24803	5.87437032
3.7	37	18.5	19.45	75.47392	5.67195103
3.8	38	19	19.3	75.66019	5.47812837
3.9	39	19.5	19.15	75.80804	5.2923412
4	40	20	19	75.91864	5.11407762
4.1	41	20.5	18.85	75.99309	4.94286963
4.2	42	21	18.7	76.03246	4.77828844
4.3	43	21.5	18.55	76.03778	4.6199404
4.4	44	22	18.4	76.01003	4.46746344
4.5	45	22.5	18.25	75.95016	4.32052389
4.6	46	23	18.1	75.85908	4.17881372
4.7	47	23.5	17.95	75.73769	4.04204809
4.8	48	24	17.8	75.58683	3.90996319
4.9	49	24.5	17.65	75.40735	3.7823143
5	50	25	17.5	75.20003	3.65887404
5.1	51	25.5	17.35	74.96566	3.5394309
5.2	52	26	17.2	74.705	3.4237878
5.3	53	26.5	17.05	74.41878	3.3117609
5.4	54	27	16.9	74.10772	3.20317849
5.5	55	27.5	16.75	73.77252	3.09787995
5.6	56	28	16.6	73.41385	2.99571494
5.7	57	28.5	16.45	73.03238	2.89654249
5.8	58	29	16.3	72.62875	2.80023032
5.9	59	29.5	16.15	72.2036	2.70665417
6	60	30	16	71.75754	2.61569718
6.1	61	30.5	15.85	71.29118	2.52724936
6.2	62	31	15.7	70.80511	2.44120706
6.3	63	31.5	15.55	70.29991	2.35747252
6.4	64	32	15.4	69.77614	2.27595349
6.5	65	32.5	15.25	69.23437	2.19656277
6.6	66	33	15.1	68.67515	2.11921796
6.7	67	33.5	14.95	68.099	2.04384102
6.8	68	34	14.8	67.50645	1.9703581
6.9	69	34.5	14.65	66.89803	1.89869915
7	70	35	14.5	66.27424	1.82879776
7.1	71	35.5	14.35	65.6356	1.76059089
7.2	72	36	14.2	64.98258	1.69401864
7.3	73	36.5	14.05	64.31567	1.62902408

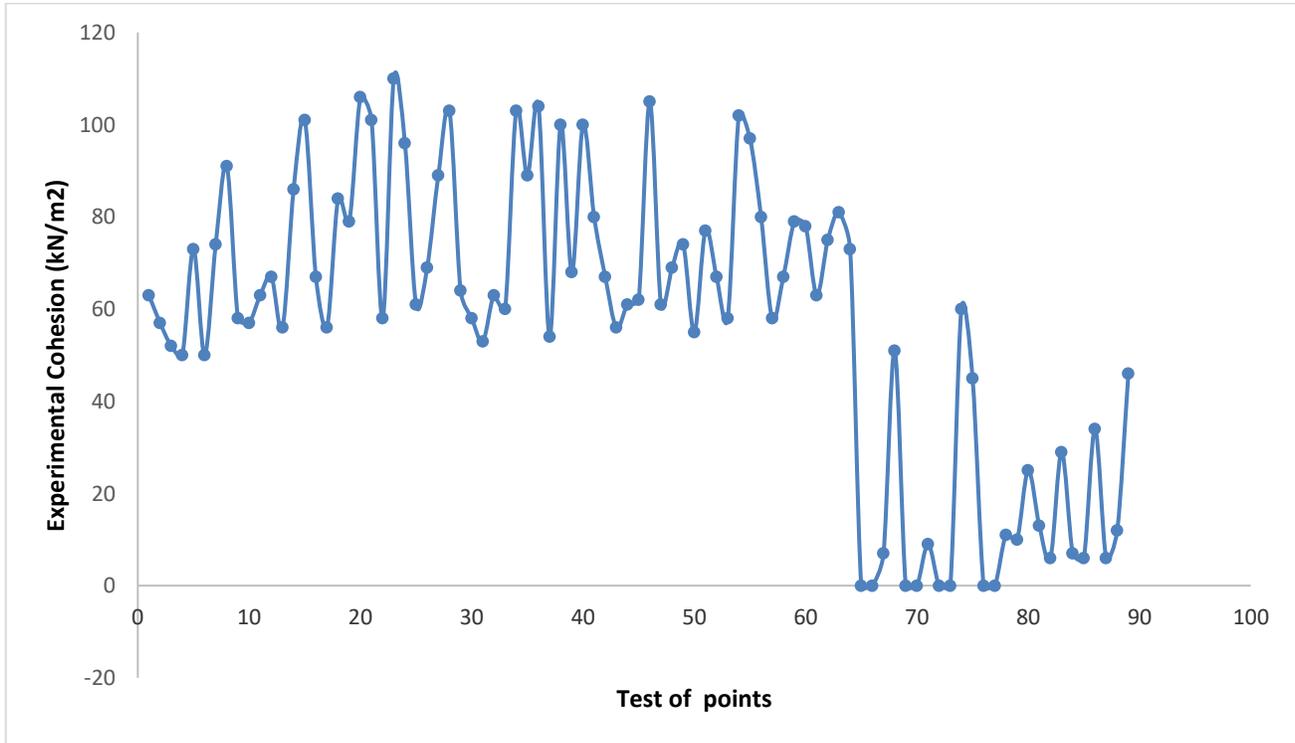


7.4	74	37	13.9	63.63537	1.56555309
7.5	75	37.5	13.75	62.94214	1.50355412
7.6	76	38	13.6	62.23644	1.4429781
7.7	77	38.5	13.45	61.51874	1.38377826
7.8	78	39	13.3	60.7895	1.32591003
7.9	79	39.5	13.15	60.04915	1.26933084
8	80	40	13	59.29815	1.21400011
8.1	81	40.5	12.85	58.53694	1.15987906
8.2	82	41	12.7	57.76595	1.10693062
8.3	83	41.5	12.55	56.9856	1.05511937
8.4	84	42	12.4	56.19633	1.00441144
8.5	85	42.5	12.25	55.39856	0.95477438
8.6	86	43	12.1	54.5927	0.90617716
8.7	87	43.5	11.95	53.77916	0.85859006
8.8	88	44	11.8	52.95836	0.81198457
8.9	89	44.5	11.65	52.13069	0.76633338
9	90	45	11.5	51.29658	0.72161032
9.1	91	45.5	11.35	50.45641	0.67779025
9.2	92	46	11.2	49.61058	0.63484907
9.3	93	46.5	11.05	48.75949	0.59276362
9.4	94	47	10.9	47.90353	0.55151167
9.5	95	47.5	10.75	47.04308	0.51107188
9.6	96	48	10.6	46.17854	0.47142371
9.7	97	48.5	10.45	45.3103	0.43254744
9.8	98	49	10.3	44.43872	0.39442411
9.9	99	49.5	10.15	43.5642	0.35703546
10	100	50	10	42.68712	0.32036397

*A. Experimental Test Results for Cohesion (Cu)*

The result for the cohesion is a representation of Cu values obtained from laboratory investigation at different points and with varying depths, liquid limit, plastic limits and unit weight, the plot showing the Cu values changing

with respect to spatial depths and the varying soil parameters at 16 boreholes points in the study areas, as shown in Fig. 1.



**Fig. 1. Experimental Test Results for Cohesion (Cu)**

**B. Experimental Test Results for Angle of Internal Friction**

The angle of internal friction ( $\phi$ ) represents values derived from laboratory investigations conducted at various depths and locations. These values were influenced by changes in liquid limit, plastic limit, and unit weight across the study area.

A plot illustrates the variability of  $\phi$  with respect to spatial depth, reflecting the different soil parameters measured at 16 borehole locations within the region as shown in Fig. 2.

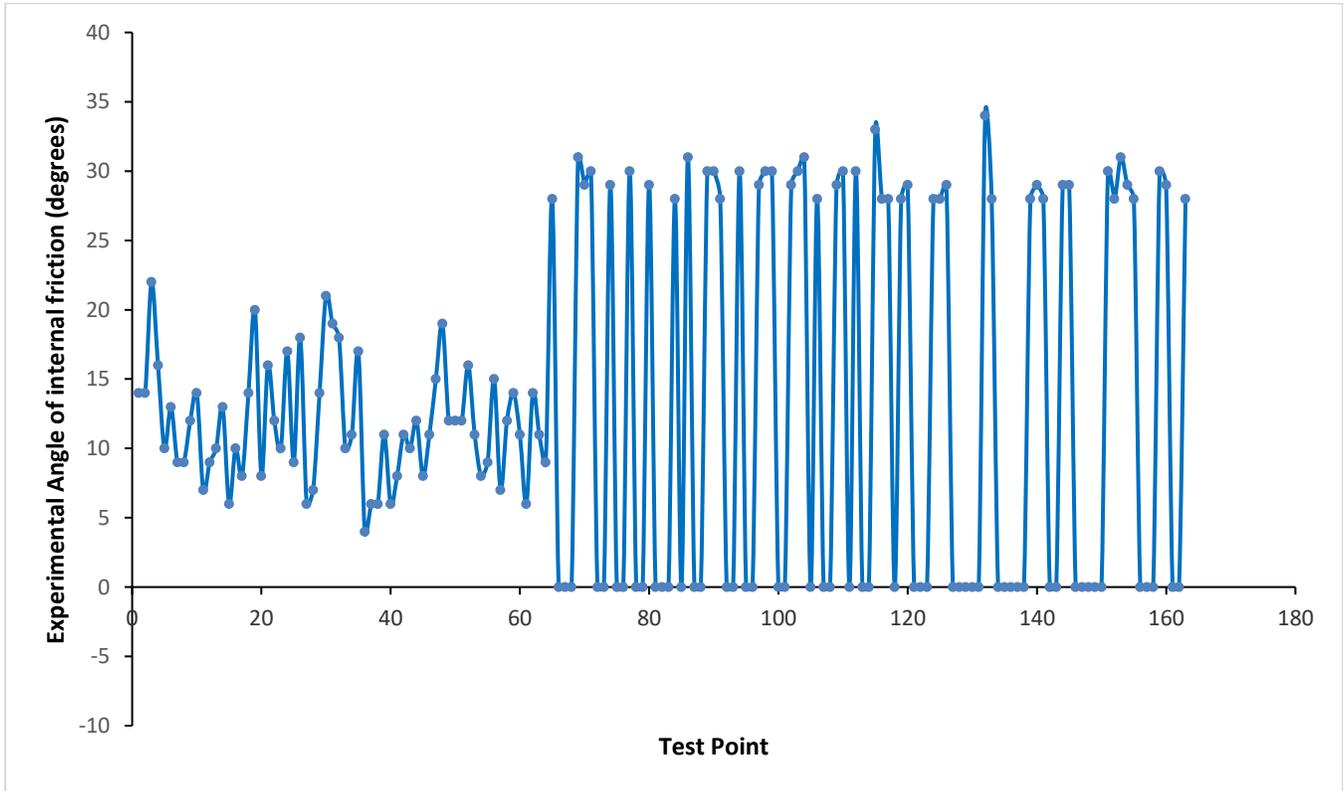


Fig. 2. Experimental Test Results for Angle of Internal friction ( $\phi$ )

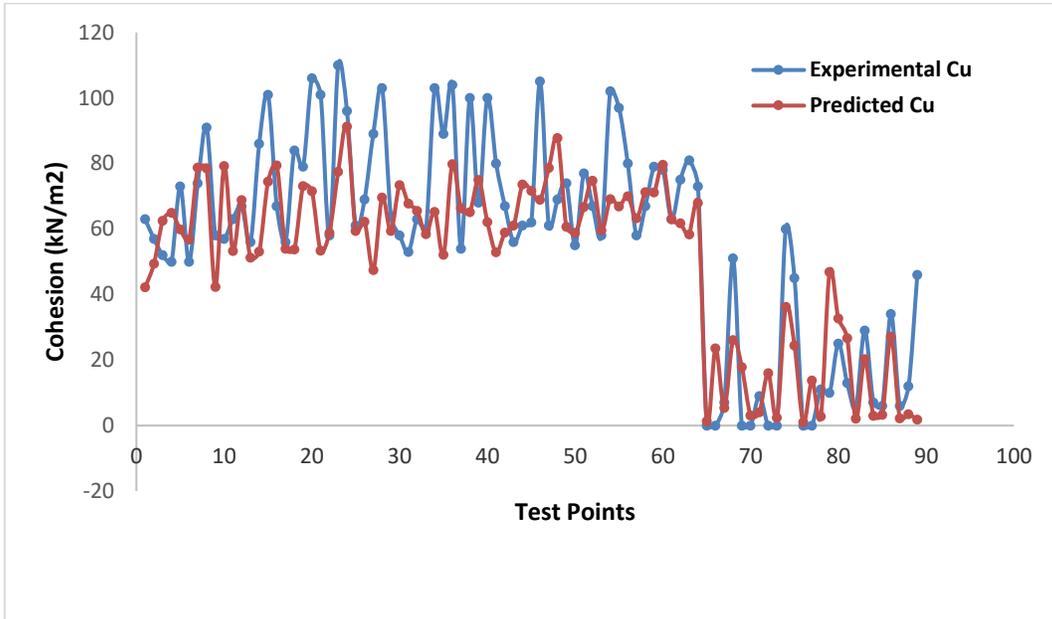
*C. Modelled Results of Cohesion And Angle of Internal Friction*

The computed values for cohesion ( $C_u$ ) and the angle of internal friction ( $\gamma$ ) were derived using empirical models as outlined in equations (7) and (8). These models were specifically developed to estimate the cohesion and angle of internal friction at any specified location, utilising experimental soil property data. The analysis was performed employing the Least Squares method, alongside Python and Microsoft Excel, facilitating both analysis and simulation processes.

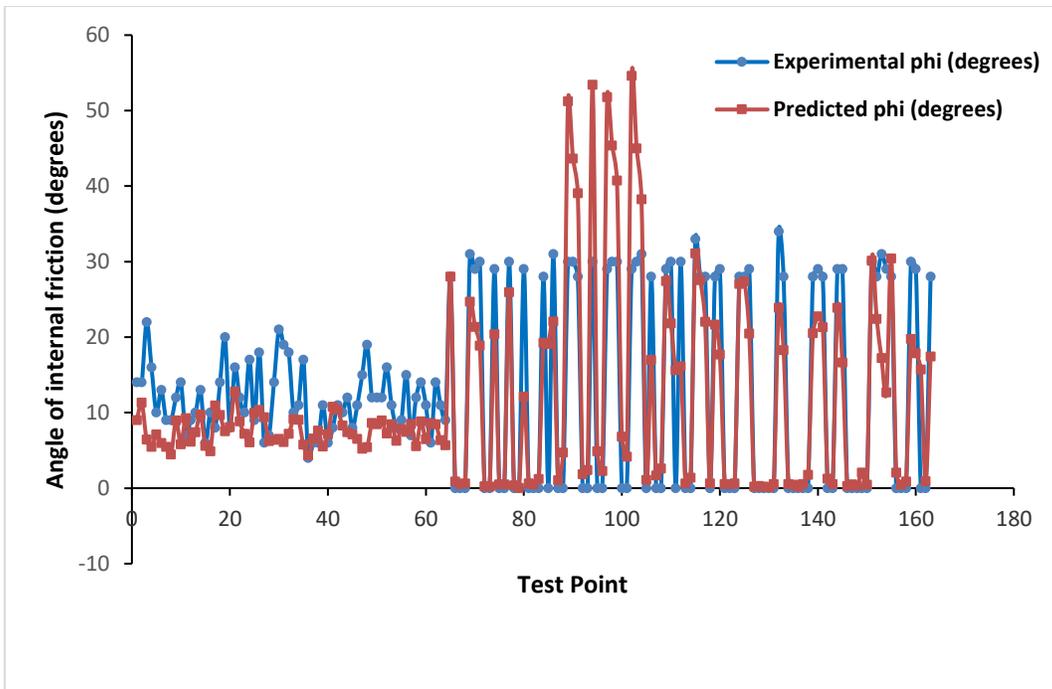
$$C_u = 0.041346(1 + D)^{0.1145}(1 + W)^{0.9489}(1 + P)^{-0.4375}(\gamma')^{1.7499} - 1 \quad (7)$$

$$\text{while } \tan(1 + \phi) = 0.04382(1 + D)^{-0.3005}(1 + W)^{-1.6362}(1 + P)^{1.1609}(\gamma')^{1.3311} \quad (8)$$

Further more the model reveals the experimental and predicted results of  $C_u$  and  $\gamma$  values shows reliability as the graphs of both experimental and predicted values are in close range as shown in Fig. 3 and Fig. 4.



**Fig. 3. Experimental Test Results for Experimental and Predicted (Cu)**

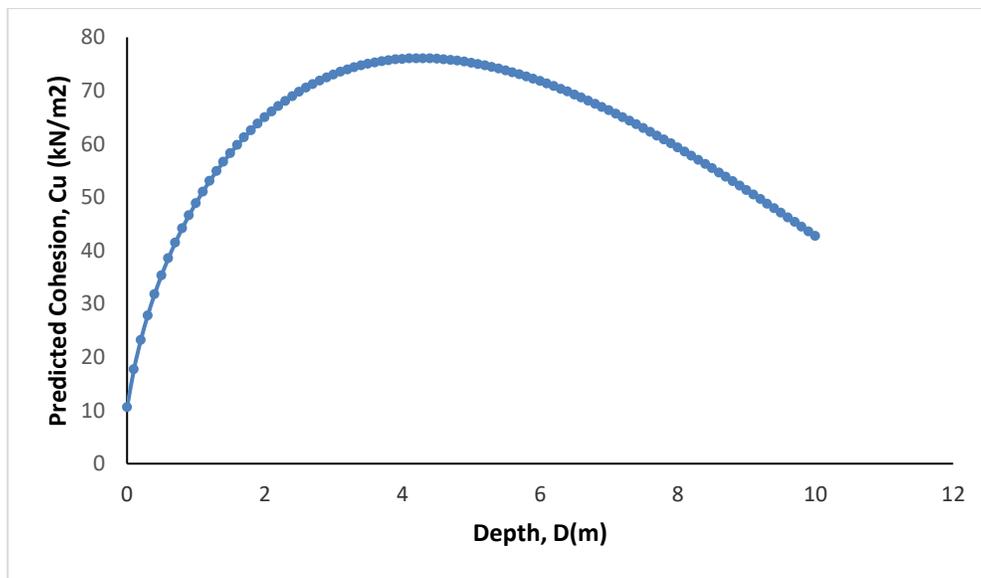


**Fig. 4. Experimental Test Results for experimental and predicted ( $\phi$ )**

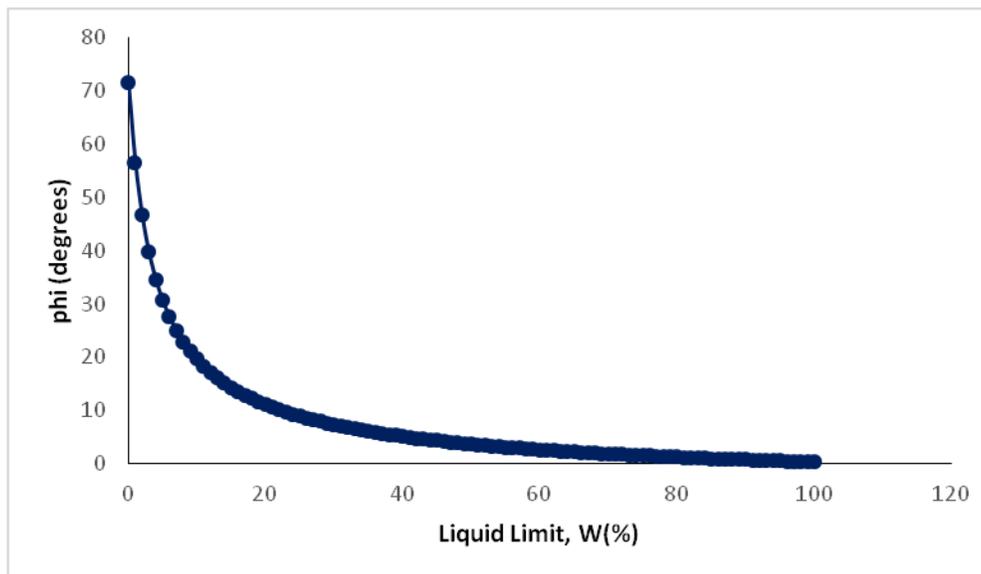
*D. Predicted results of Decrease in Effective Unit Weight, Increase in Liquid Limit, Plastic Limit and Depth.*

The observed decrease in effective unit weight, alongside the increase in liquid limit and plastic limit, resulted in a significant correlation with higher cohesion ( $C_u$ ) values and reduced friction angle ( $\phi$ ) values. This trend was consistent across various arbitrary points and depths of investigation.

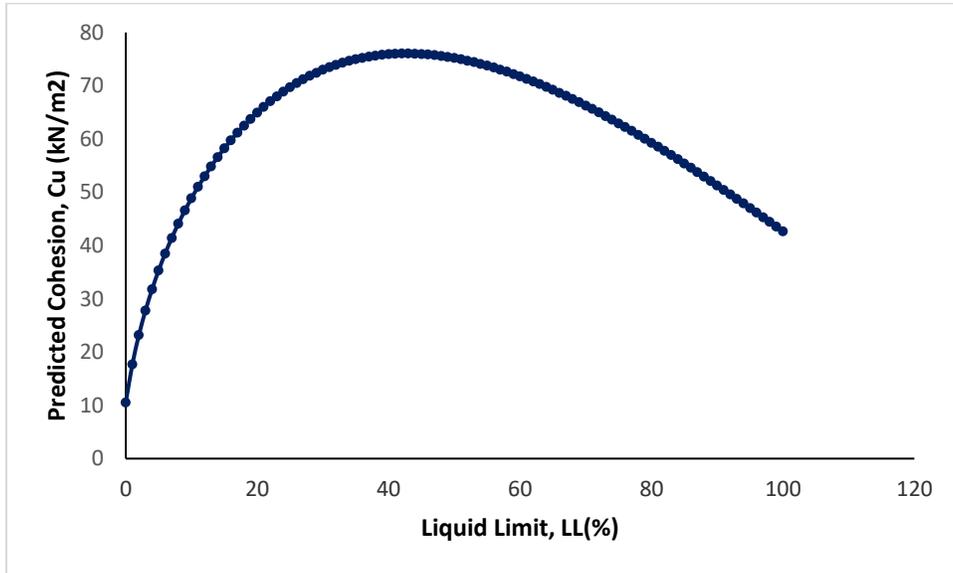
At a depth of 4.1m, the liquid limit (LL) recorded was 41, plastic limit (PL) was 20.5, and the unit weight ( $\gamma$ ) measured at 18.8, yielding  $C$  and  $\phi$  values of 75.9 and 4.94, respectively. At a depth of 8.3m, the values shifted to LL at 83, PL at 41.5, and  $\gamma$  at 12.5, resulting in  $C$  and  $\phi$  values of 56.9 and 1.05, respectively. Finally, at a depth of 9.4m, the measurements indicated LL at 94, PL at 47, and  $\gamma$  at 10.9, yielding  $C$  and  $\phi$  values of 47.9 and 0.55, respectively. These findings are summarized in figure 5-12



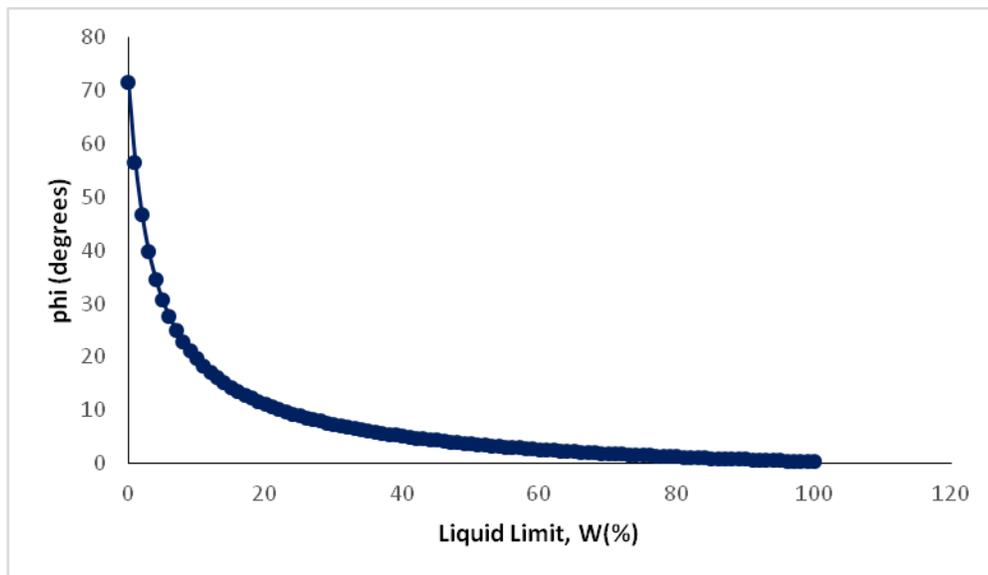
**Fig 5. Prediction of cohesion with increase in depth (d)**



**Fig 6. Prediction of angle of internal friction with increase in liquid limit (LL)**



**Fig 7. Prediction of cohesion with increase in liquid limit (LL)**



**Fig 8. Prediction of angle of internal friction with increase in liquid limit (LL)**

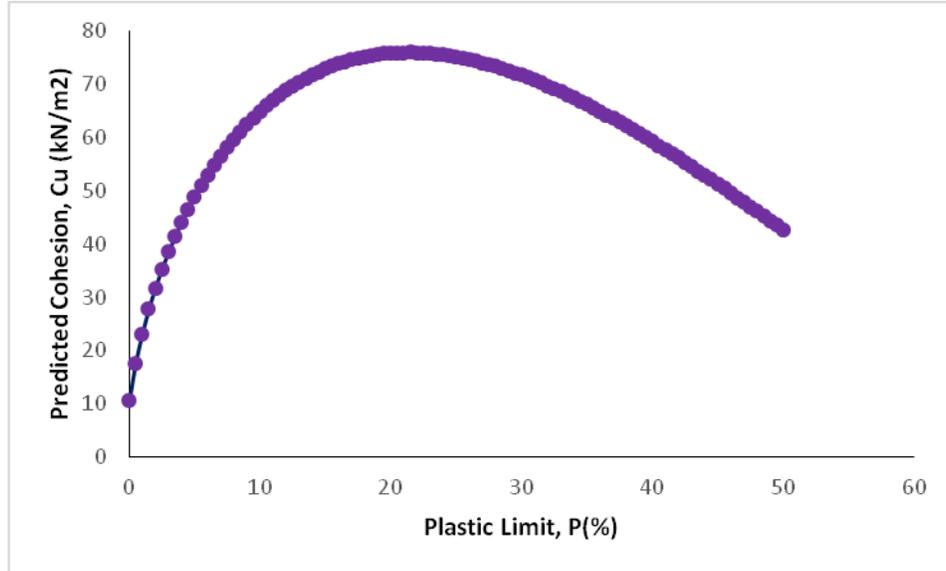


Fig 9. Prediction of cohesion with increase in plastic limit (PL)

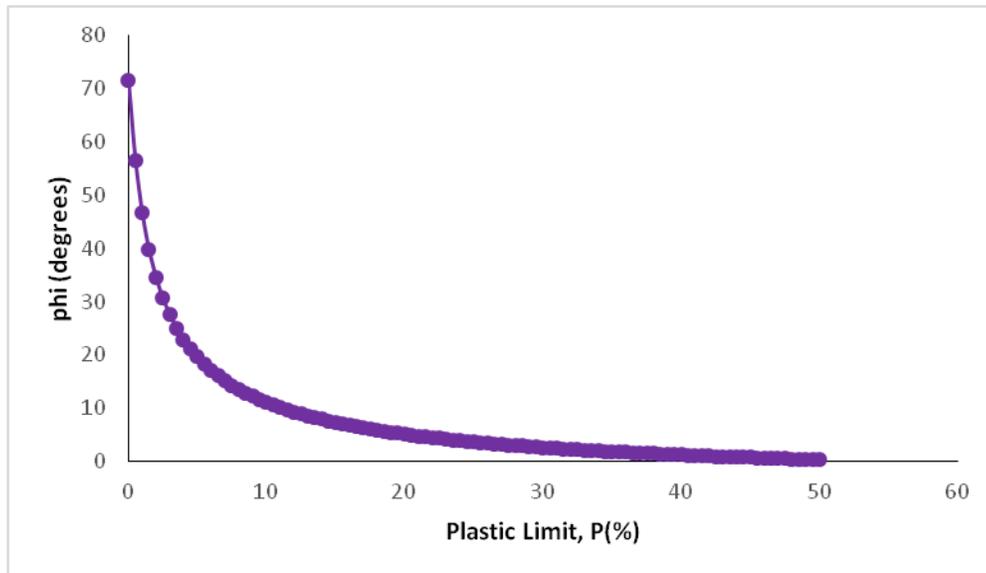


Fig 10. Prediction of angle of internal friction with increase in plastic limit (PL)

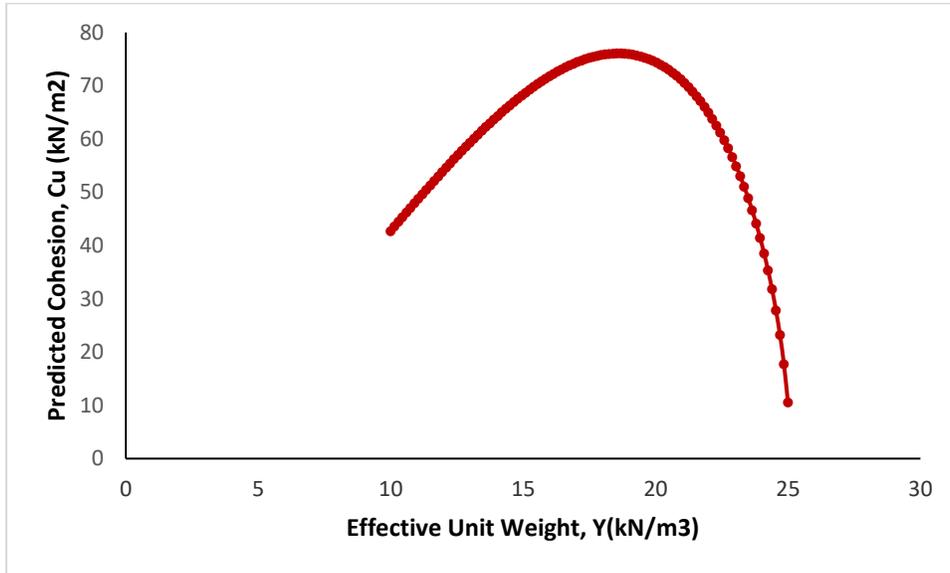


Fig 11. Prediction of cohesion with decrease in effective unit weight ( $\gamma$ )

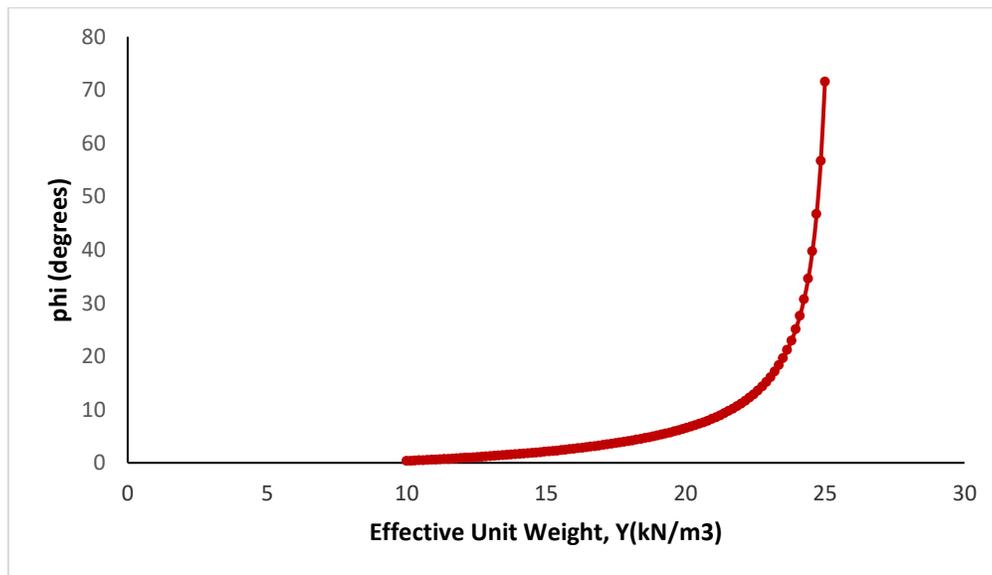
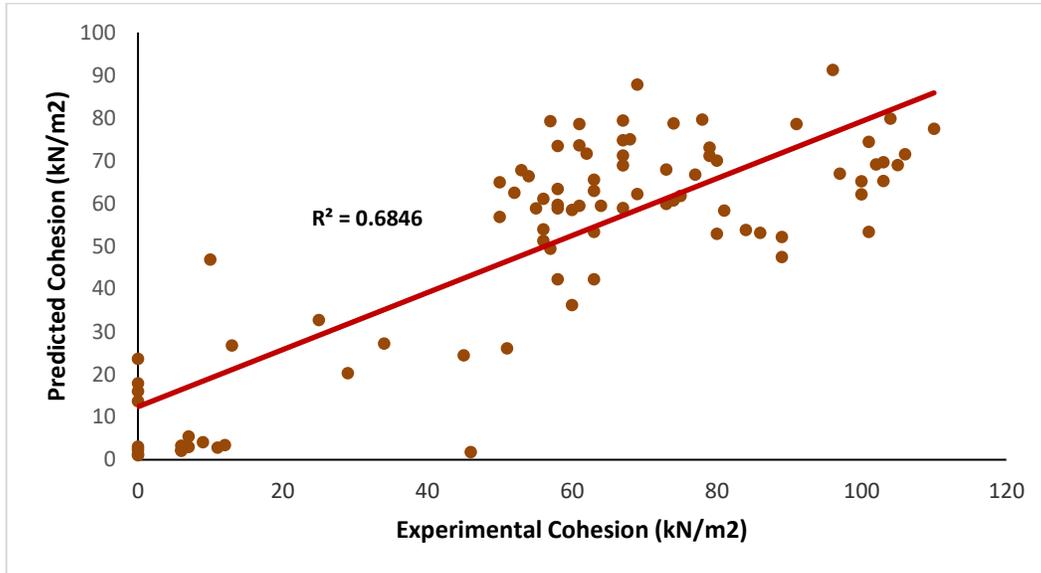


Fig 12. Prediction of angle of internal friction with decrease in effective unit weight ( $\gamma$ )

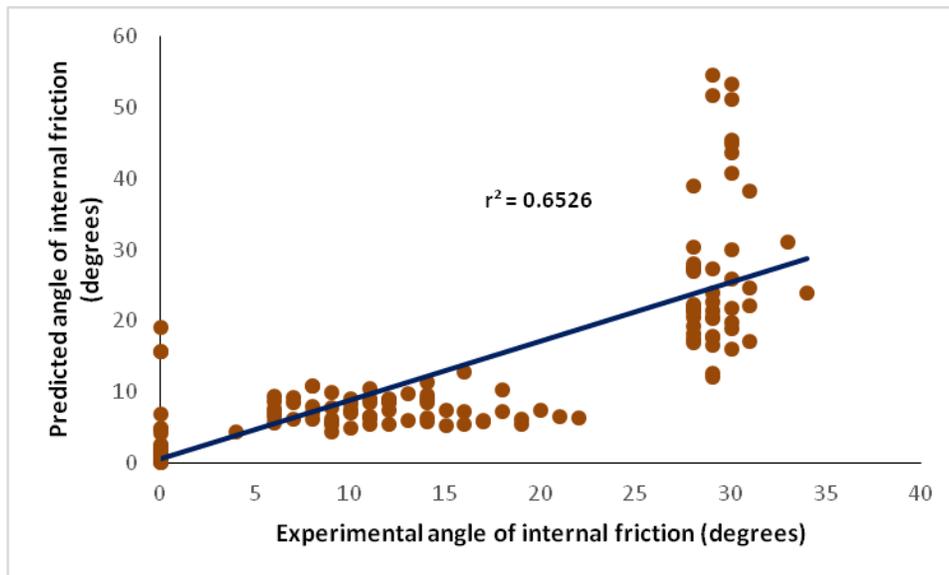
#### E. Model Validation

The coefficient of correlation for the experimental and predicted cohesion ( $C_u$ ) across all points and depths,  $r^2 = 0.6846$ , indicating a significance level of 68.4%, compared to coefficient of correlation for the experimental and

predicted angle of internal friction ( $\phi$ ),  $r^2 = 0.6526$ , which translates to a significance level of 65.2%. These results reflect a robust correlation, approaching 70% significance threshold and demonstrating a strong degree of reliability in the research.



**Fig. 13. Correlation coefficient of the experimental and predicted cohesion (Cu)**



**Fig. 14. Correlation coefficient of the experimental and Internal Friction**

### VII. CONCLUSION

The study has demonstrated that modeling in geotechnical engineering can effectively utilise statistical methods, Microsoft Excel, and sophisticated computer modeling tools, such as Python, which was employed in this research. The investigations has established that the model performed reliably, highlighting how experimental soil results can be used to predict reliable geotechnical properties for design purpose.

This model establishes a methodology for conducting site-specific investigations through the Least Squares method, implemented in Python software, to determine the undrained cohesion (Cu) and angle of internal friction ( $\phi$ ) values of soil at any given site. It also facilitates rapid estimation of the field's undrained cohesion and angle of internal friction at various depths based on the corresponding soil parameters integrated into the model.



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The study established the direct relationship between index properties, such as liquid limit, plastic limit, alongside the unit weight of soil and depth, as decreasing liquid limit, plastic limit, and increasing effective unit weight, with depth significantly affect the  $C_u$  and  $\phi$  values of the soil. There is an increasing demand for the determination of subsurface geotechnical properties for design purposes. However, the costs associated with field investigations have hindered the practice of exploring greater depths and additional locations on-site.

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