UNCERTAINTY AND RELIABILITY ASSESSMENT OF UCS IN FIBER-ENHANCED CLAYEY SOILS

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Abstract:
Fiber reinforcement is a widely adopted technique for improving the mechanical behavior of clayey soils, particularly in enhancing their Unconfined Compressive Strength (UCS). However, the variability in soil properties, fiber content, mixing uniformity, and environmental conditions introduces uncertainties in the strength outcomes. This study presents a reliability-based assessment of UCS performance in fiber-reinforced clayey soils using statistical and probabilistic tools. Laboratory experiments were conducted using synthetic fibers at varying dosages, and the resulting UCS data were analyzed for mean strength, standard deviation, and coefficient of variation. A reliability analysis was performed using the First-Order Second-Moment (FOSM) method and Monte Carlo simulations to evaluate the probability of failure under different design thresholds. The results demonstrate the importance of incorporating uncertainty modeling in geotechnical design and confirm that fiber reinforcement, while effective, exhibits strength outcomes with significant variability. This study supports the development of more risk-informed soil stabilization practices in geotechnical engineering.

I. INTRODUCTION

In geotechnical engineering, the use of fiber reinforcement in clayey soils has emerged as an effective ground improvement technique, particularly for increasing shear strength, tensile resistance, and ductility. Among its advantages, Unconfined Compressive Strength (UCS) serves as a key indicator of performance in stabilized soils. However, UCS behavior in fiber-reinforced clayey soils is influenced by numerous factors including fiber type, length, content, soil plasticity, compaction effort, and moisture conditions. These variables introduce considerable uncertainty in strength prediction, which conventional deterministic design approaches often fail to capture.

Modern geotechnical design increasingly recognizes the need to consider uncertainty and variability through reliability-based methods, which evaluate the probability of failure rather than just a safety factor. By applying tools such as statistical distribution fitting, FOSM, and Monte Carlo simulations, engineers can better understand the risks associated with soil behavior under variable conditions.

This study aims to bridge the gap between experimental soil improvement and probabilistic design by investigating the reliability of UCS performance in fiber-reinforced clayey soils. Through a combination of experimental testing and statistical modeling, we analyze how the introduction of synthetic fibers affects not only average strength but also its dispersion and failure risk. The findings provide insight into optimizing fiber dosage and quality control measures to achieve consistent and reliable soil stabilization outcomes.

2. METHODOLOGY

2.1 TESTS CONDUCTED

The soil sample for the investigation came from Anantapur, which is located in Andhra Pradesh. After the soil has been gathered, it was left to air-dry for some time, and then it was pulverised into fragments that were 4.75 millimetres in size.

Dry and wet sieve analysis tests were conducted in order to get a better idea of the grain size distribution.

It was determined what the specific gravity of the soil was, as well as its Atterberg limits. physical properties of the soil were analysed which are reported in Table 1.

After that, the results of standard proctor tests were used to determine the optimal moisture content and maximum dry density of soil samples that had not been treated and soil samples that had been treated with lime. Both sets of samples were tested using the same conditions.

In order to determine how different lengths of steel fibres (20mm and 30mm), amounts of steel fibres (0.2,0.4, and 0.6% dosage by weight of soil), and curing periods (0,7,28, 60,120, and 160 days) affected the UCS when lime was present at a concentration of 9% by weight of soil, research was conducted. According to the findings, the length of the steel fibres was the factor that had the most significant impact on the UCS. Soil samples were cured by using plastic wraps with the help of an adhesive tape.

After that, the results of the experiments were incorporated into an artificial neural network (ANN) model for the purpose of making predictions.

Weight of the soil, the amount of water and lime content, the number of curing days, and the dosages and lengths of the steel fibres were used as input (predictor) variables in our study. UCS values obtained in the laboratory tests are taken as the output value or target value to predict the UCS fit values.

In this particular piece of research, artificial neural networks, also known as ANNs, were educated with the help of an algorithm called Feed Forward Back Propagation (FFBP). Training, testing, and validation of data were carried out during the process of back propagation training, and as a result, good correlations with scores greater than 97% were achieved as a result.

There is a perfect correlation between the experimental results and the prediction of the unconfined compressive strength based on ANN, with very low mean square errors in both cases. This is due to the fact that ANN is able to model the experimental data very accurately.

After that, a different combination of input data is provided in order to discover the predicted UCS values directly without performing the UCS experiment.

It is hypothesised that the effect will vary depending on the dosage as well as the length of the steel fibres (40mm, 50mm, or 15mm). Therefore, UCS values are predicted for fibre reinforced soil with length of 40 mm, 15 mm, and 50 mm using the employed predictive model.

The findings demonstrated a strong correlation which can be observed in Figure 5. while exhibiting low error rates; consequently, this model is suitable for use in predicting the outcomes for a diverse range of combinations of data.

(a) (b) (c)

Figure 1: (a) Standard proctor test; (b) Preparation of soil sample for UCS test.(c)Soil specimen after failure.

2.2. UNCONFINED COMPRESSIVE STRENGTH OF SOIL

Unconfined Compressive Strength (UCS) stands for the maximum axial compressive stress that a cohesive soil specimen can bear under zero confining stress. Unconfined compression test is one of the fastest and cheapest methods of measuring shear strength of clayey soil.

Unconfined Compressive Strength (UCS) is the load per unit area at which an unconfined cylindrical specimen of soil will fail in the axial compression test. If the axial compression force per unit area has not reached a maximum value even at 20 percent axial strain, the UCS shall be taken as the value obtained at 20 percent axial strain.

APPARATUS REQUIRED

Compression Device

The loading device shall have sufficient capacity and strain controlled. It may be any of the following type:

a) Platform weighing scale equipped with a screw-jack activated yoke.

b) Hydraulic loading device.

c) Screw jack with a proving ring; and

d) Any other loading device.

Figure 2: Unconfined Compressive Strength testing machine.

Proving Ring

For soils with UCS less than 100 KPa, load shall be measurable to 1 KPa. For soils with UCS greater than or equal to 100 KPa, load shall be measurable to nearest 5 KPa.

Deformation Dial Gauge, having a least count of 0.01mm and travel to permit not less than 20 percent axial strain.

Vernier Callipers, having least count of 0.1mm.

Timing device, to indicate the elapsed testing time to the nearest second may be used for establishing the rate of strain.

Oven, thermostatically controlled with interior of non-corroding material and capable of measuring 1100 ± 50 C.

Weighing Balances, with least count of 0.01g if the specimen weight is less than 100g or least count of 0.1g if the specimen weight is equal to more than 100g.

Miscellaneous Equipment: Specimen trimming and carving tools, remolding apparatus, water content cans etc.

2.3. PREPARATION OF TEST SPECIMEN

Specimen Size: The specimen shall have a minimum diameter of 38mm and the largest particle in the specimen shall be smaller than 1/8 of the specimen diameter. After completion of test on the undisturbed sample, if it is found that the larger particles than permitted are present, it shall be noted in the report of test data under remarks. The height to diameter ratio shall be within 2 to 2.5.

Undisturbed Specimens:

Undisturbed specimens shall be prepared from large undisturbed samples or samples secured in accordance with IS 2132: 1986.

When samples are pushed from the drive sampling tube the ejecting device shall be capable of ejecting the soil core from the sampling tube in the same direction of travel in which the sample entered in the tube and with negligible disturbance of the sample. Conditions at the time of removal of the sample may dictate the direction of removal, but the principal concern should be to keep the degree of disturbance negligible.

Remolded Specimen:

The specimen may be prepared either from a failed undisturbed specimen or from a disturbed soil sample. In the case of failed undisturbed specimen, the material shall be wrapped in a thin rubber membrane and thoroughly worked with the fingers to assure complete remolding. Care shall be taken to avoid entrapped air, to obtain a uniform density, to remould to the same void ratio as that of the undisturbed specimen and to preserve the natural water content of the soil.

Compacted Specimen:

When compacting disturbed material, it shall be done using a mould of circular cross-section

Compacted specimen may be prepared at any predetermined water content and density. After the specimen is formed, the ends shall be trimmed perpendicular to the long axis and removed from the mould. Representative sample cuttings shall be obtained, or the entire specimen shall be used for the determination of water content after the test. Then to perform UCS test:

- The initial length, diameter and weight of the specimen shall be measured, and the specimen placed on the bottom plate of the loading device. The upper plate shall be adjusted to make contact with the specimen.
- The deformation dial gauge shall be adjusted to a suitable reading, preferably in multiples of 100. Force shall be applied so as to produce axial strain at a rate of 0.5 to 2 % per minute causing failure

with 5 to 10. The force reading shall be taken at suitable intervals of the deformation dial reading.

The specimen shall be compressed until failure surfaces have definitely developed, or until an axial strain of 20% is reached.

Stress-strain values shall be calculated as follows:

a) The axial strain(e) shall be determined from the following relationship:

$e = \Delta L / L0$ (1)

Where:

ΔL = the change in the specimen length as read from the strain dial indicator, Lo= the initial length of the specimen.

b) The average cross-sectional area (A), at a particular strain shall be determined from the following relationship:

$A = A0 / (1-e)$

(2)

Where:

A0 the initial average cross-sectional area of the specimen.

c) Compressive stress ($\sigma 0$), shall be determined from the relationship:

$\sigma 0 = P/A$ (3)

Where:

P= the compressive force, and A= average cross-sectional area.

The maximum stress gives the value of the unconfined compressive strength (qu). In case no maximum occurs within 20% axial strain, the unconfined compressive strength shall be taken as the stress at 20% axial strain.

In the case of soils which behave as if the angle of shearing resistance Ø=0 (as in the case of saturated clays under undrained conditions) the undrained shear strength or cohesion of the soil may be taken to be equal to half the unconfined compressive strength obtained in Para above.

3.RESULTS & DISCUSSION

Table 1: Physical properties of soil

Physical properties	Values
1. Specific Gravity	2.6
2. Liquid limit (%)	58.4
3. Plastic limit (%)	31
4. Plasticity index (%)	27.4
5. Soil type	CH
6. Optimum Moisture Content (untreated soil sample)	16.2 %
7. Maximum Dry Density (untreated soil sample)	1.79 g/cc
8. Optimum Moisture Content (lime treated soil sample)	18.7 %
9. Maximum Dry Density (lime treated soil sample)	1.83 g/cc

Table 2: Percentage of soil fraction

Type	Percentage
Gravel	0.4
Sand	5
Silt	75.8
Clay	18.8

Table 2 shows the percentage of soil fraction.The grain-size distribution of the soil was found by carrying out both wet sieve and dry sieve analyses per IS 2720 (BIS 1980) and the type of the soil was found as CH.

Table 3: UCS for lime (9%) and fibre treated soil samples

Length of fibers	Percentage of steel fibers	UCS (kn\m^2) values for different curing periods					
		0 (Day)	7 (Days)	28 (Days)	60 (Days)	120 (Days)	160 (Days)
	0	52.7	63.4	88.94	230.52	180.2	72.3
20 mm	0.2	53.1	64	90.2	233.2	182.34	90.3
	0.4	61.2	70	100	240.5	194.2	85.6
	0.6	52.02	63	87	230.4	102.3	76.4
30 mm	0.2	51.03	61	87.1	160.5	100.01	72.1
	0.4	50	59	75.6	123.2	95.3	62.3
	0.6	48.2	52.4	63.2	112.4	90.2	60.1

Table 3 represents unconfined compressive strength values for both conventional as well as fiber and lime inclusive soil samples for the above curing days.

Effect of 20mm fibers on UCS:

From the UCS tests, it is clear that the strength of the soil improves nominally as the percentage of steel fiber increases up to 0.4%, whereas there is a reduction in UCS at 0.6% of steel fibers of 20mm length and with the increase in curing period UCS also increases up to 60 days and drastically decreased after 60 days. Optimum Values are obtained at 0.4% of steel fibers and for 60 days curing for 20mm steel fibers as shown in Table 3 and also the variation of UCS can be observed in the graphical representation which is shown in fig.3.

Effect of 30mm fibers on UCS:

The strength of the soil decreases as the percentage of steel fiber increases in the case of 30mm steel fibers. From the Table 3 it is clear that, UCS decreases drastically with the increase in curing days which can also be observed from graphical representation which is shown in fig.4.

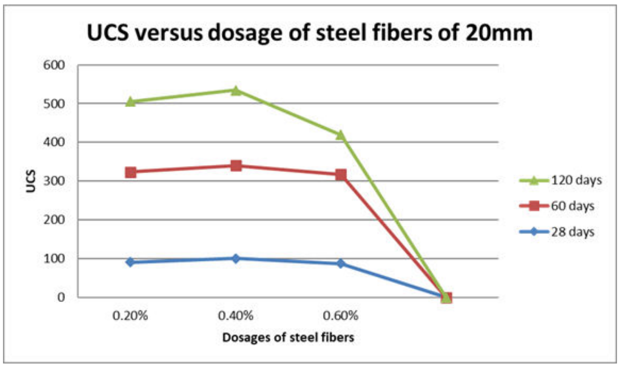

Figure 3: UCS versus dosage of fibers (20mm).

Figure. 3 shows the variation of UCS at different percentages of steel fibers of 20mm for different curing days.

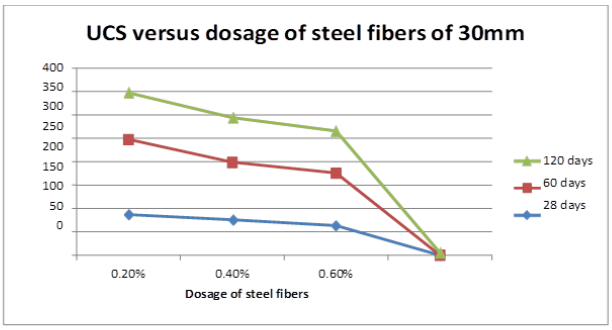

Figure 4: UCS versus dosage of fibers (30mm).

Figure. 4 shows the variation of UCS at different percentages of steel fibers of 30mm for different curing days.

Table 4: Trained experimental input data and predicted output values with errors in ANN

s.no	soil weight	water content	lime content	curing days	fiber length	fiber dosage	UCS kn m2	UCS kn m2 Predicted	Errors ploted
1	100	18.7	9	0	0	0	52.7	52.6943	0.00556248
2	100	18.7	9	0	20	0.2	53.1	53.20123	-0.1012
3	100	18.7	9	0	20	0.4	61.2	61.052	0.148
4	100	18.7	9	0	20	0.6	52.02	52.153	-0.133
5	100	18.7	9	0	30	0.2	51.03	51.02856	0.0014
6	100	18.7	9	0	30	0.4	50	49.86542	0.1346
7	100	18.7	9	0	30	0.6	48.2	48.2931	-0.0931
8	100	18.7	9	7	0	0	63.4	63.35621	0.04379
9	100	18.7	9	7	20	0.2	64	64.0235	-0.0235
10	100	18.7	9	7	20	0.4	70	69.7654	0.2346
11	100	18.7	9	7	20	0.6	63	62.8893	0.1107
12	100	18.7	9	7	30	0.2	61	60.9945	0.0055
13	100	18.7	9	7	30	0.4	59	59.4321	-0.4321
14	100	18.7	9	7	30	0.6	52.4	52.3995	0.0005
15	100	18.7	9	28	0	0	88.94	88.93999745	2.54639E-06
16	100	18.7	9	28	20	0.2	90.2	90.16509575	0.034904253
17	100	18.7	9	28	20	0.4	100	99.99999991	9.46438E-08
18	100	18.7	9	28	20	0.6	87	86.99999978	2.17419E-07
19	100	18.7	9	28	30	0.2	87.1	87.10794744	-0.007947437
20	100	18.7	9	28	30	0.4	75.6	75.59999987	1.33466E-07
21	100	18.7	9	28	30	0.6	63.2	63.20000005	-4.71385E-08
22	100	18.7	9	60	0	0	230.52	230.4762945	0.043705479
23	100	18.7	9	60	20	0.2	233.2	233.9533007	-0.75330068
24	100	18.7	9	60	20	0.4	240.5	240.4943004	0.005699564
25	100	18.7	9	60	20	0.6	230.4	230.5000619	-0.100061926
26	100	18.7	9	60	30	0.2	160.5	160.4818655	0.018134547
27	100	18.7	9	60	30	0.4	123.2	123.2333303	-0.033330283
28	100	18.7	9	60	30	0.6	112.4	112.4320169	-0.032016869
29	100	18.7	9	120	0	0	180.2	180.2863788	-0.086378836
30	100	18.7	9	120	20	0.2	182.34	182.5833629	-0.243362925
31	100	18.7	9	120	20	0.4	194.2	194.2875991	-0.08759914
32	100	18.7	9	120	20	0.6	102.3	101.9118676	0.388132441
33	100	18.7	9	120	30	0.2	100.01	99.63565827	0.374341728
34	100	18.7	9	120	30	0.4	95.3	95.35321575	-0.053215754
35	100	18.7	9	120	30	0.6	90.2	90.2442302	-0.044230195
36	100	18.7	9	160	0	0	72.3	72.29997782	2.21792E-05
37	100	18.7	9	160	20	0.2	90.3	90.30005988	-5.98777E-05
38	100	18.7	9	160	20	0.4	85.6	85.60001733	-1.73254E-05
39	100	18.7	9	160	20	0.6	76.4	76.42210427	-0.022104271
40	100	18.7	9	160	30	0.2	72.1	72.14915643	-0.049156426
41	100	18.7	9	160	30	0.4	62.3	62.30000846	-8.45833E-06
42	100	18.7	9	160	30	0.6	60.1	60.10000207	-2.07081E-06

The UCS predicted values shown in the above table were obtained by training the experimental data in ANN. Above table shows all the input data considered to train the network and also the errors obtained to ensure efficiency of the training.

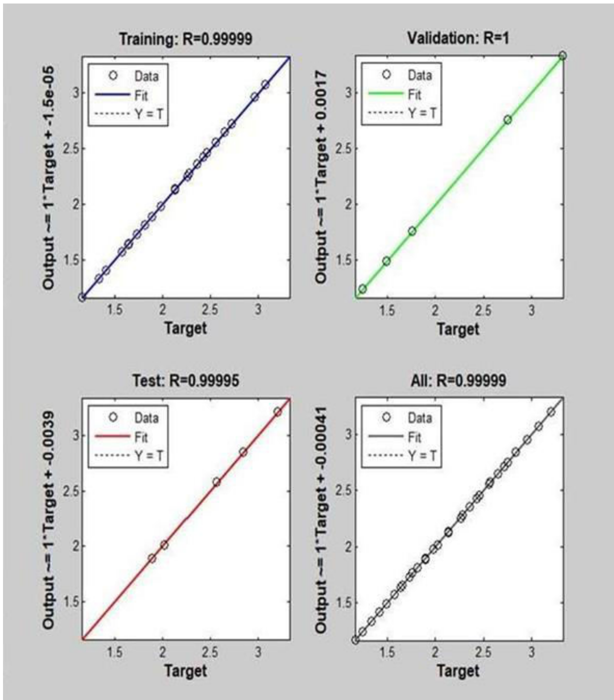

Figure 5: Regression plot.

Figure 5 shows Regression plots for training, testing and validation of ANN in MATLAB. Network is trained multiple times till the R is almost equal to one. R is the coefficient of correlation which shows how well our predicted outputs are matching with real outputs. From fig.5 we can say that our trained network is good.

Table 5: UCS predicted values for different input combinations from past data.

s.no	soil weight	water content	lime content	curing days	fiber length	fiber dosage	UCS kn/m2 Predicted
1	100	18.7	9	28	40	0.2	79.82
2	100	18.7	9	28	40	0.4	72.4
3	100	18.7	9	28	40	0.6	63.05
4	100	18.7	9	28	50	0.2	61.05
5	100	18.7	9	28	50	0.4	59.0432
6	100	18.7	9	28	50	0.6	59.0222
7	100	18.7	9	60	40	0.2	113.0432
8	100	18.7	9	60	40	0.4	112.4681
9	100	18.7	9	60	40	0.6	111.0321
10	100	18.7	9	60	50	0.2	110.2915
11	100	18.7	9	60	50	0.4	107.5432
12	100	18.7	9	60	50	0.6	100.172914
13	100	18.7	9	120	40	0.2	90.3924146
14	100	18.7	9	120	40	0.4	89.643865
15	100	18.7	9	120	40	0.6	83.58693336
16	100	18.7	9	120	50	0.2	82.64833
17	100	18.7	9	120	50	0.4	79.2711932
18	100	18.7	9	120	50	0.6	75.49452
19	100	18.7	9	160	40	0.2	60.053852
20	100	18.7	9	160	40	0.4	59.9051099
21	100	18.7	9	160	40	0.6	57.7936
22	100	18.7	9	160	50	0.2	55.12199
23	100	18.7	9	160	50	0.4	50.4947867
24	100	18.7	9	160	50	0.6	47.7556787
25	100	18.7	9	28	15	0.2	85.4231
26	100	18.7	9	28	15	0.4	87.2493
27	100	18.7	9	28	15	0.6	80.2229
28	100	18.7	9	60	15	0.2	100.2364
29	100	18.7	9	60	15	0.4	102.3546
30	100	18.7	9	60	15	0.6	98.54621
31	100	18.7	9	120	15	0.2	95.15321
32	100	18.7	9	120	15	0.4	95.56842
33	100	18.7	9	120	15	0.6	88.94321
34	100	18.7	9	160	15	0.2	76.241
35	100	18.7	9	160	15	0.4	70.32149
36	100	18.7	9	160	15	0.6	68.76439

Table 5 contains UCS predicted values for different input combinations as shown above. The UCS values were obtained according to the training of past experimental data. Feed Forward Backdrop Algorithm is used. according to the table as fiber length and dosage of fiber increases, UCS decreases.

4.CONCLUSION

This research highlights the importance of incorporating uncertainty and reliability analysis into the performance assessment of fiber-reinforced clayey soils. Experimental results confirm that fiber addition improves average UCS values; however, the associated variability in strength due to heterogeneity in fiber distribution, soil properties, and test conditions necessitates a probabilistic approach for design validation.

The FOSM and Monte Carlo simulation techniques applied in this study revealed significant fluctuations in the probability of failure across different fiber contents and target strength thresholds. These outcomes emphasize that while fiber reinforcement enhances overall soil strength, deterministic evaluations alone are insufficient for safe geotechnical design under uncertain conditions.

In conclusion, this study supports the adoption of reliability-based frameworks in soil stabilization projects, especially when using fiber reinforcement in clayey soils. Future work may explore the effect of natural fiber alternatives, field-scale validation, and machine learning-based prediction models to further refine risk-informed geotechnical design practices.

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