Strength prediction models for fiber-reinforced soils under effective stress triaxial compression testing

K. E. Bantralexis[1*], *A. G.* Vassou[1] *and I. N.* Markou[1]

[1]Democritus University of Thrace, Department of Civil Engineering, University Campus - Kimmeria, GR-67100 Xanthi, Greece

Abstract. The improvement of shear strength of soils is a common practice applied in numerous civil engineering projects. Geosynthetics like geogrids, geotextiles and fibers contribute significantly in soil strength improvement. Soil reinforcement with randomly oriented fibers has attracted extensive research attention. The shear strength of fiber-reinforced soils is often determined experimentally by performing triaxial compression tests under effective stress conditions. Presented in this paper are easy-to-use models for the strength prediction of fiber-reinforced soils under the aforementioned testing conditions. After an extensive literature review, a database of 436 measurements was created including data for all independent variables relative to the soil and fiber characteristics. This database was then processed and divided into two subsets: the first, consisting of 75% of the measurements, was used to develop the models by performing statistical analyses, whereas the second, with the remaining 25% of the measurements, served as a basis for their validation. The development of the models was achieved through multivariable linear regression analyses performed with suitable statistical software. After an extensive number of trials, three optimal models were derived that satisfy the statistical requirements, exhibiting R^2 determination coefficients greater than 0.95 and satisfactory estimation of the validation measurements at a rate reaching 81%.

1 Introduction

Geotechnical engineering is a field of civil engineering of major importance, and it is devoted to the thorough study, observation and investigation of soil formations. Although the soil exhibits resistance to compressive stresses, it indicates weakness in dealing with tensile forces. In order to address this weakness, Geotechnical Engineering focuses on the development of soil reinforcement methods. The incorporation of tensile-resistant materials

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[*] Corresponding author: kbantral@civil.duth.gr

into the soil leads to the creation of a new, reinforced soil composite. Reinforced soil stands out for its improved engineering characteristics, such as increased shear strength, improved elasticity, reduced permeability and limited deformability. The reinforcement of soil formations with fibers is a common practice in the field of geotechnical engineering. This method aims towards the shear strength and the deformability improvement of the soil. In multiple civil engineering projects, engineers are called upon to deal with unsuitable soils, as it is difficult to find a soil or soil formation with the desired mechanical properties [1]. Reinforced soil is defined as soil that has been improved by a material capable of resisting tensile stresses and that interacts with the soil through friction. Fiber-reinforced soil, therefore, is a soil reinforcement technique, in which the soil is mixed with an appropriate amount of fibers to improve its mechanical characteristics [2].

The inclusion of fibers into the soils has three main functions: a) The improvement of the shear strength and Bearing Capacity of the soil, b) Reduction of settlements, c) Reduction of lateral deformations. The fibers used to reinforce soils may be natural, derived from vegetable materials such as coir, sisal or jute, or artificial, made from materials such as polypropylene, polyester or glass. In addition, fibers are classified according to their geometric shape, which may be circular, rectangular or triangular. Finally, the fibers are classified into single, multifilament, fibrillated and 'tape' type fibers. The material properties of multiple type of fibers have been quantified by researchers in the past few years [3, 4].

The soil improvement can be quantified by performing multiple laboratory tests, such as the Triaxial Compression testing which measures shear strength parameters and deformability of the fiber reinforced soil. Over the decades, many researchers have performed Triaxial Compression Tests in fiber reinforced soils in various versions a) Unconsolidated Undrained (UU), b) Consolidated Undrained (CU), c) Consolidated Drained (CD), the last two versions measure the shear strength of fiber reinforced soils under effective stress conditions. The literature review indicates that CU Triaxial Compression Tests are mainly performed in clays [5-9] and CD tests in sands or granular materials [5, 10-12].

Many researchers proposed models by utilizing their personal database in order to predict the shear strength of fiber reinforced soils. The utilization of these models aims to facilitate the reliable design and enhance the utilization of fiber-reinforced soils in civil engineering projects. The majority of these models are produced by performing statistical analysis [13, 6, 14], probabilistic analysis [15] or by analytical solutions [16]. Some researchers have also developed alternative type of models, such as fuzzy linear regression models [17] or Neural Network models [12] for shear strength prediction of fiber reinforced soils. In most cases, the development of these models was based solely on the experimental results of the same research effort and the produced models refer to specific type of soil, i.e. sand or clay. Also, some of these models cannot be applied easily as they employ parameters difficult to determine.

The above-mentioned information indicates that a practical tool could be an efficient means for shear strength prediction of fiber-reinforced soils. The investigation reported herein aims towards the development of this practical tool in the form of easy-to-use models which will combine the following characteristics: a) the model is applicable to any type of soil, b) the independent variables that the model includes are based on simple parameters pertinent to the soil and fiber. In the first part of this presentation, a large database comprising experimental measurements from Triaxial Compression Tests under effective stress conditions which emerged from extensive literature review, will be analyzed. In addition, the development of the new prediction models by performing multivariable ordinary (conventional) linear regression analyses of the obtained experimental results will take place. Finally, the performance of the proposed models is documented in the last part of this presentation, accompanied by comparative conclusions.

2 Experimental measurements

To record the data of each test from the available laboratory investigations, a database was created, which would facilitate the gathering of the data of interest and their subsequent evaluation and input into the statistical software. For each measurement collected to the database the following parameters were included: a) reference, b) type of Triaxial Compression Testing, c) type of soil, d) fiber characteristics, e) confining pressure σ_3, f) major principal stress at failure σ'_1 of the unreinforced soil, g) major principal stress at failure σ'_1 of the fiber reinforced soil, h) deformability characteristics (elasticity modulus). Once the database was completed, after consulting empirical models proposed in previous studies for the estimation of shear strength parameters of the fiber-reinforced soil, a selection of the most suitable parameters which will serve as independent and dependent variables took place in order to create the empirical models presented in this study. The evaluation of soil mechanical properties is based on multiple Triaxial Compression testing versions, CD (Consolidated Drained) and CU (Consolidated Undrained) tests are the most used types. The choice of the appropriate method depends on key characteristics such as soil type and available time to perform the test. In sandy soils, both CD and CU versions are performed. In contrast, in clayey soils, the CU method dominates, with CD being used less frequently, considering its time-consuming nature. Table 1 presents a summary of the available data that were utilized for this research. This table mostly contains range of values for the parameters that were analyzed above.

The results of the literature review presented in Table 1 also indicate that different soils, ranging from poorly graded sands to high plasticity clays, were investigated in the preceding research efforts in combination with a wide variety of synthetic and natural fibers with lengths, L_f, between 5 mm and 50 mm. It is observed that the effects of soil and fiber type on the mechanical behavior of fiber-reinforced soils have not been methodically or adequately examined in the past as only one or a limited number of soil or fiber types were used in each investigation. Although the fiber length and content have been investigated more extensively in previous research efforts (Table 1), their effect on the shear strength parameters of fiber-reinforced soil is ambiguous, possibly due to differences in the tested materials and, as a result, it needs further experimental documentation.

Researchers are also studying the orientation of fibers in test specimens to identify the optimal arrangement. In specimens with a horizontal fiber orientation, strength is significantly increased. The reason lies in the effective absorption of tensile stress by the fibers, which act as reinforcing elements along their entire length. Although, in specimens with a vertical fiber orientation, the strength is significantly reduced. This phenomenon happens due to the inability of the fibers to absorb the tensile stress in the same manner. In specimens with random fiber orientation, the strength is in the intermediate range.

Table 1. Data of selected research studies based on Triaxial Compression tests.

Ref.	Soil Type	Fiber Characteristics *^{2}						Triaxial Parameters		
		Material	D mm	A_r	σ_{yf} MPa	L_f mm	W_f %	σ'_3 kPa	σ'_{1u} kPa	σ'_{1r} kPa
[7]	CL	Tape	4	2	-	8	0.25-2	200	380	358-385
[6]	CL	CF	0.24*^{3}	50-150	10,1	12-36	0.5-2	100	369-575	272-281
[24]	Sand^{*1}	C	0.09	266-400	1100	24,36	0.5	20-400	75-1474	96-2063
[11]	SM	CW	5	1-9	0.8	5-45	0.4-1.2	100	394-398	430-530
[31]	SP	PP	0.1*^{3}	120-500	120	12-50	0.5	20-550	359	470-774
[28]	SM	OPEFB	0.4*^{3}, 0.51*^{3}	37.5 -112	283, 306	15-45	0.25, 0.5	250	312-770	369-1073
[29]	Sand^{*1}	PW	4	3	-	12	0.5-1	100	254	286-338
[27]	Sand^{*1}	PW	4	3	-	12	0.5-1	100	256, 705	291-905
[25]	Sand^{*1}	PP	0.1*^{3}	500	120	50	0.5	20-200	40-932	395-1757
[26]	CH	PP	4	15.7	350	63	0.2	50-500	186-898	211-764
[34]	SP	PP	0.03*^{3}	375	400	12	0.3-0.8	50-200	84-429	109-527
[19]	SP	PVA	0.1*^{3}	120	1078	12	0.5,1	50-500	219-2307	342-3504
[8]	Clay	CF	0.8*^{3}	38.6	8.2	30.9	0.5-3	100-400	306-933	260-1042
[36]	CH	PP	0.018	666	610	12	0.25	50-300	132-917	149-1029
[35]	SP	PVA	0.04*^{3}	300	1560	12	0.2, 0.4	50-600	221-2390	249-2743
[32]	Sand^{*1}	CF	0.25*^{3}	60	102	15	0.5-2	100	283	328-484
[5]	SP, CL	PP	-	-	425	25, 50	0.2, 0.4	70-140	188-532	186-1081
[30]	SP	PP	-	-	310	51	0.4	140	343-1494	1033-2815
[33]	SM	PP	-	-	310	50	0.4	69	305-742	1028-1085
[37]	SP	C	-	-	38.4 - 464.8	25	0.5	50-150	186-507	225-901

*^{1}: USCS symbols not included in this column are not available in the relevant references. *^{2}: PP: Polypropylene, OPEFB: Oil palm empty fruit bunch, CW: Carpet waste, PW: Plastic waste, C: Curaua fiber, CF: Coir fiber, PVA: Polyvinyl alcohol fiber. *^{3}: Circular fiber.

The random distribution of fibers, although not offering the maximum possible strength, it simulates realistic conditions. In conclusion, fiber orientation plays a key role in the strength of a specimen. These conclusions are based on the findings of Michalowski and Cermak [18]. It is noted that the database presented in Table 1 includes fibers with random distribution inside the specimen for this research effort.

An important qualitative characteristic studied in the paper was the type of fiber used for soil reinforcement. As part of the research, a variety of fiber types were identified and classified into two categories: natural and artificial. Natural fibers include coconut fibers, Curaua (a rainforest plant), plant roots, cotton, and in other research efforts referred to as natural fibers without precise identification. In contrast, artificial fibers include polypropylene, polyamide (nylon), PVA (polyvinyl alcohol), waste tyres, steel fibers from waste carpets and fibers from recycled plastic water bottles. As for the geometry of these fibers, circular and rectangular synthetic fibers are presented in Table 1.

Taking into consideration the above mentioned information, the dependent variable of the equation is determined as the major principal stress at failure of the reinforced soil σ'_{1r} (effective Stress of Reinforced Soil, kPa) while the independent variables that were chosen are pertinent to the soil type and the fiber and are the following: a) The fiber aspect ratio (ratio of the fiber length to its equivalent diameter), A_r, b) the length of the reinforcing fiber, L_f (mm), c) the tensile strength of the fiber, $\sigma_{,y\ f}$ (kPa), d) the fiber content by weight , W_f (%), e) The strength of soils can be quantified by multiple parameters due to the great variety of soil types which were utilized in this study. In addition, the consideration of soil strength can become more complex by taking into account the different parameters affecting it, depending on the gradation of these soils. Therefore, for simplicity reasons, the major principal stress at failure of the unreinforced soil σ'_{1u} (effective Stress of Unreinforced Soil kPa) was defined as the independent variable that represents indirectly the variety of soil types.

Table 2. Datasets for each independent variable combination.

Independent variables combination	Total dataset measurements	Processed dataset measurements	
σ_{1u}'(kPa), W_f (%), $\sigma_{y,f}$ (kPa)	288	202	
		152 (model)	50 (testing)
σ_{1u}' (kPa), W_f (%), L_f (mm)	307	173	
		130 (model)	43 (testing)
σ_{1u}' (kPa), W_f (%), A_r	173	173	
		130 (model)	43 (testing)

It is therefore clear that the data series that could be used as input in the statistical software would necessarily have to contain complete data for all of the above variables. Also, these datasets in order to be processed statistically for model development, have to include at least 20 measurements for each independent variable used in the model [20, 21, 22]. At the same time, a processed data set was formed, which includes only qualitative data, by excluding possible inappropriate measurements. As a result, the initial database was reduced to this used for statistical analysis. In addition, 3 possible combinations of the above variables were considered in this study. Each combination resulted in a total dataset containing complete sets of measurements and the final processed dataset which resulted after excluding inappropriate measurements and was utilized for the statistical analysis, is indicated in Table 2. A percentage equal to 75% of the data presented in Table 2 was used for the generation of the model, whereas the remaining 25% of measurements were used for the evaluation of the prediction efficiency of the model.

3 Development and efficiency of models

The preparation of the database of the experimental measurements and the selection of the appropriate dependent and independent variables were followed by the statistical analysis. For the purposes of this research, the multivariable ordinary linear regression (MVOLR) method was applied, in order to produce simple-to-use models for the prediction of the major principal stress at failure of fiber reinforced soils by utilizing Triaxial Compression Tests. A large number of analyses were performed for each one of the three combinations of independent variables that were presented in Table 2, using a special statistical software. The models that will be presented in this section, were developed by applying the multivariable ordinary linear regression method to a set of data and have the following form:

$$y=\alpha_0+\alpha_1x_1+\alpha_2x_2+\cdots+\alpha_nx_n \tag{1}$$

where y is the dependent variable, α_0, α_1,…, α_n are the partial coefficients and x_1, x_2,…, x_n are the independent variables.

The statistical analysis dictates that the data should be checked for independence and regularity of observations, linearity between dependent and independent variables, equality of dispersion as well as for the assumption of multi-collinearity and singularity [23]. In addition, the Durbin – Watson index indicates the verification of independence, which should attain values between 1.0 and 3.0 [21]. The regularity, linearity and dispersion equality were checked using the relevant graphs provided by the software. The existence of multi-collinearity and singularity is not desirable in the analyses and was checked by using the eigenvalue of the covariance matrix, the condition index, the tolerance interval and the variance inflation factor. Finally, the levels of statistical significance (p-value) for each variable as well as the value of t-statistics were checked in all analyses. The p-value must be lower than 5% and the absolute value of t-statistics must be greater than 2. Apart from the aforementioned statistical checks, the credibility of models was also attested by the high values of the coefficient of multiple determination, R^2.

The resulting models were also tested for their prediction efficiency utilizing, as stated above, a percentage equal to 25% of the total set of measurements. The predicted values, $\sigma_{1r}'{}_{\mathrm{predicted}}$ (effective Stress of Reinforced Soil) were estimated by applying the models to these testing measurements. The deviation, Δ (%), of the predicted values from the experimental values, $\sigma_{1r}'{}_{\mathrm{measured}}$, was then calculated as follows:

$$\Delta\,(\%)=\frac{\sigma1r'measured-\sigma1r'predicted}{\sigma1r'measured}\cdot 100 \tag{2}$$

The predicted values presenting deviation equal to or less than ±20% are considered acceptable. By finding the total number of acceptable values, the prediction efficiency of each model was obtained for the testing measurements as follows:

$$Efficiency\ (\%) = \frac{total\ number\ of\ acceptable\ values}{total\ number\ of\ measurements} \cdot 100 \tag{3}$$

Table 3 presents the three best models that were produced after statistical analysis using the MVOLR method. Each model is suitable for each one of the three independent variable combinations that were analyzed in section 2. The table also contains the R^2 values which range in high levels from 0.946 to 0.976, indicating the statistical importance of models.

The models satisfy the statistical checks as analyzed in detail above, all p-values are lower than 5% and all absolute values of t-statistics are greater than 2. The Durbin-Watson factor ranges between 1 and 3. The efficiency of the models is also presented in the last part of Table 3, by applying the models to the testing measurements datasets. The structure of the models is simple and they do not contain constant value, which complicates the regression analyses and reduces the statistical performance. It is obvious that the prediction efficiency of models presenting very high R^2 values, is large if the measurements used for model development are utilized. Therefore, it is common practice for the credibility of prediction efficiency not to use in model testing the measurements utilized for model development. Accordingly, prediction computed with the Equations 2 and 3, is also satisfactory as it is ranges from 68% to 81.4%. The performance of all models is also depicted in Figure 1 where the estimated values of effective stress at failure of fiber-reinforced soil, σ'_{1r}, are compared to those determined experimentally. It is confirmed that 34, 35 and 30 of the 50, 43 and 43 predicted values, respectively, lie within the area set by the acceptable deviation of ±20% from the testing measurements. Although the prediction efficiency of model 2 is the best compared to the other two models, it was decided to present all models in this study to facilitate their choice depending on the available measurement parameters.

Table 3. Proposed models for predicting effective stress of fiber reinforced soils.

No.	Model	R^2	Efficiency (%)
1	$\sigma_{1r}{}' = 1.219 \cdot \sigma_{1u}{}' + 0.345\, \sigma_{yf}{}^{0.4} - 0.264 \cdot (W_f * 3)^3$	0.946	68% $(\frac{34}{50})$
2	$\sigma_{1r}{}' = 1.251 \cdot \sigma_{1u}{}' - 7.678 \cdot \frac{e^{L_f}}{10^{26}} - 1.868 \cdot \frac{(W_f \cdot 3)^3}{10}$	0.972	81.4% $(\frac{35}{43})$
3	$\sigma_{1r}{}' = 1.226 \cdot \sigma_{1u}{}' + 0.359 \cdot Ar - 93.832 \cdot ABS[Ln(W_f)]$	0.976	69.8% $(\frac{30}{43})$

4 Conclusions

This research effort aims at the development of empirical relationships for the prediction of strength of fiber-reinforced soils. By following the in-depth analysis and examination of the issues carried out in the previous sections, the following conclusions can be reported:

- The literature review has shown that the optimum fiber percentage for achieving maximum strength of a soil is not constant. On the contrary, it varies and depends

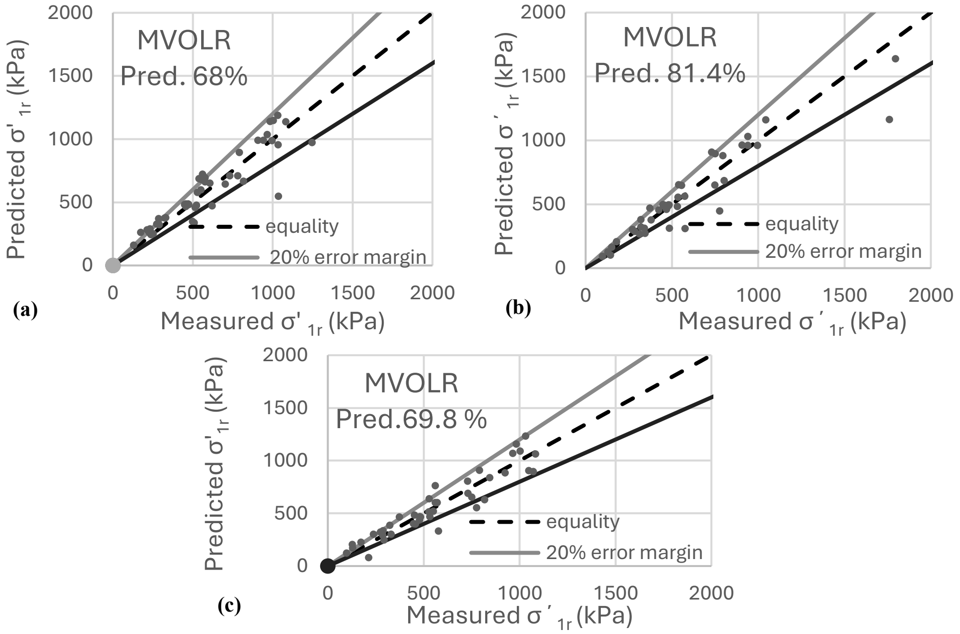

Fig 1. Performance of prediction model: (a) 1, (b) 2, (c) 3 (testing data).

on the nature of the soil and the type of fiber. Therefore, an increase in fiber content does not necessarily imply a corresponding increase in strength. However, an optimum content seems to be adopted between 0.5 and 1 %.

- The resulting optimal models are characterized by statistical adequacy, as the statistical indicators that characterize them reach high levels. R^2 exceeds 0.94 in all models, indicating a strong interpretation of the dependent variable by the independent variables. The model efficiency ranges from 67.4 to 81.4, confirming the reliability of the models. Furthermore, all models have a zero constant term as testing models with a non-zero constant term yielded much worse results.
- It was found that the length of the fiber presents a more significant effect on the prediction of strength than its tensile strength and aspect ratio. The efficiency of the model verifies that statement, as it indicates the highest percentage compared to the other optimal models.
- The models do not seem to indicate reduced prediction efficiency according to the soil type or fiber characteristics. A slight overestimation of the predicted values of the maximum principal failure stress at low levels and an underestimation at high levels, compared to the experimental values, was observed for the models with aspect ratio and those with fiber tensile strength.
- These models can be utilized for every type of soil reinforced with fibers (natural or synthetic, rectangular or circular). Apart from their accuracy and reliability, the implemented models are distinguished for their simplicity, small size and satisfactory efficiency rates. Therefore, through their simple structure, they ensure easy use.

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