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Determining the Suction Capacity of Compacted Clays with Fuzzy-Set Theory

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Abstract
Water suction capacity is an important parameter affecting soil's swelling properties and volumetric change. The water suction capacity is determined through time-consuming laboratory experiments. However, this has random errors due to the heterogeneous and anisotropic structure of the soil sample together with the error caused by the operator made the experiment. Solving such an estimation problem including error can be easily achieved using fuzzy-set theory. In this study, we use fuzzy-set theory to predict the suction capacity of compacted clayey soils. For this reason, the engineering properties of clayey soil (plasticity index, dry density, initial water content, and suction capacity) are partitioned into fuzzy subsets, and fuzzy rules are formed. Later, a computer program in the Fortran language is written to estimate the suction capacity of compacted clayey soil from these properties. It is shown that there is a good similarity between the results of the tests and the proposed fuzzy logic model.

1. Introduction

The suction of soils is known as the free energy of soil water. The water suction capacity of soil is also described as water holding ability [1], [2], [3]. In clays with high absorption capacity, a significant increase in volume and pressure occurs due to soil-water reaction. Engineering structures built on these soils may suffer important damage from soil water, such as a few floored light structures, highway and airport pavements, pipelines, or retaining walls. In such cases, determining the suction capacity and pressure of clayey soil at the start of construction allows necessary precautions to be taken, reducing potential problems. For this reason, many researchers have worked to determine the suction capacity and pressure by experimental and theoretical studies.

In general soil suction has two components; namely matric and osmotic suction. For many practical studies in geotechnical engineering, a variation in total suction is equivalent to a variation in the matric suction [4]. Suction is a parameter that shows the mechanical behavior of soil, controlled by the matric suction. [5]. An increase in soil suction increases the shear strength of soil based on the effective angle of internal friction and cohesion [6]. In addition, the deformation modulus of soil is a function of effective stress and suction [7]. In the literature, there is a significant amount of research on predicting the shear strength, deformation modulus, and permeability of soils for soil suction [8], [9].

Suction pressure and capacity of soils depend on soil properties such as soil type, dry density, initial water content, plasticity index, consistency limits, fabric, void ratio, flow velocity, etc. [10]. It was stated that the value of suction capacity rises with increasing liquid limit in the studies that searched for a relationship between the suction capacity and liquid limit [11], [12]. In studies searched the relationship among soil suction, dry density, and void ratio, it is shown that suction rises with an increase in dry density, and that suction falls with the increase in void ratio [13]. Studies between suction capacity and initial water content show that suction capacity falls

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with increasing water content [14]. In addition, the water retention curves at different temperatures show that suction tends to reduce with increasing temperature of constant water content [15].

The literature shows the effects of soil suction on factors such as initial water content, dry density, and consistency limits. Therefore, initial water content, dry density, and plasticity index are selected as the main factors affecting suction capacity for estimation of suction capacity in this study. These factors can be determined with the experiments in the laboratory, easily.

There is a risk factor, caused by uncertainty, in geotechnical engineering practice [16]. Soil is composed of solids, liquids, and gases. The solid phase may be mineral, organic matter, or both. Thus, soil has a heterogeneous and anisotropic structure. Due to these properties, soil media involves uncertainties and unknown engineering parameters. In uncertainty problems, the fuzzy-set theory has been used recently. First, Zadeh [17] introduced the concept of fuzzy sets to describe uncertainty. The works used the fuzzy-set theory also exist in geotechnical engineering. Fuzzy sets were used to determine the capacity of single piles into sand [18]. Juang et al. [19] presented a qualitative evaluation scheme for mapping the slope failure potential using a fuzzy-set analysis. Juang et al. [20], explained how to determine the relative density of sands from the cone penetration test (CPT) using the fuzzy sets. They implied that there is a good agreement between the results of the fuzzy model and CPT. A fuzzy approach was used to determine soil classification from CPT results [21]. A fuzzy-set-based approach was used for determining characteristic values of measured geotechnical parameters [22], [23]. Researchers implied that a nonlinear model and non-unimodal functions with the fuzzy-deviation method provided the most conservative results.

The intelligent learning algorithms of ANN, Fuzzy Logic, GEP, ANFIS, ANOVA, and other nature-inspired algorithms have been reviewed as they are applied in predicting geotechnical and geo-environmental problems and systems. They are complex exercises conducting experimental protocols for the design of earthwork infrastructures. Mostly, such experimental exercises don’t meet the required conditions for sustainable design and construction. At other times, certain errors resulting in experimental setup and human misjudgment, may mar the accuracy of measurements and release unexpected emissions. Most lapses encountered in repeated laboratory measurements may be solved using evolutionary learning methods [24].

There are a lot of studies using fuzzy logic in the geotechnical engineering literature: Landslide risk assessment [25], slope stability analysis of earth dams [26], tunneling geomechanics [27], rock slope stability analysis [28], retaining wall stability [29], safe bearing capacity for settlement criteria for clayey soils [30], suitability of soils in airfield applications [31], engineering properties of granular soil with wastes for environment protection and road base use [32], prediction of unconfined compressive strength of microfine cement injected sands [33] can be given as examples.

This paper aims to determine the suction capacity of compacted clay using the fuzzy-set theory. For this reason, suction capacity tests were made on compacted clayey soil samples using the oedometer test equipment. The parameters affecting the suction capacity are considered as initial water content, dry density, and plasticity index of the clay. The input and output parameters are divided into fuzzy subsets. A fuzzy rule base with if-than rules has been created. The rule base is modeled in the Fortran language. The results obtained from modeling were compared with the experimental results.

2. Material and Method

2.1. Experimental Study

Sieve and hydrometer analysis, consistency limits, pycnometer, and standard compaction tests are made on the three clay samples at ASTM Standards. Soil classes are determined and some engineering properties of the soils are given in Table 1. The Table shows that the classification of samples is high plasticity clay and that the plasticity index of samples is 54%, 47%, and 38%, respectively.

Table 1. Properties of soil samples [34]

Properties	Sample 1	Sample 2	Sample 3
Liquid limit (%)	75	73	66
Plastic limit (%)	21	26	28
Plasticity index (%)	54	47	38
Shrinkage limit (%)	7	13	10
Specific gravity	27.4	27.7	28.1
Max. dry density (kN/m^3)	16.1	16.0	15.2
Opt. water content (%)	23	23	27
Gravel (%)	1	1	0
Sand (%)	6	3	2
Silt + Clay (%)	93	96	98
Color	Grey	Red	Red
Soil classification	CH	CH	CH

Clay soil samples are sieved using a No. 40 sieve and dried in an oven for 24 hours. Samples are mixed with the pure water at different initial water contents. Prepared samples with various water contents are compacted at different dry densities in oedometer rings having 7.1 - 7.5 cm in diameter and 1.6 – 2 cm in height. It is capillary-provided saturating the samples that are placed into an oedometer cell. Hence, the final water content is determined and so this water content is considered as a suction capacity. The suction capacity test results are presented in Table 2. In this table, it is seen that 6 different dry densities (11.5 kN/m^3, 13.0 kN/m^3, 14.0 kN/m^3, 15.0 kN/m^3, 16.0 kN/m^3, 17.0 kN/m^3) and 6 different initial water contents (15%, 20%, 25%, 30%, 35%, 40%) exist. As seen from Table 2, the value of suction capacity reduces with the increase of the dry density and initial water content while it rises with the increasing plasticity index.

Table 2. Results of tests [34]

γ_d (kN/m^3)	W_0 (%)	W_{suc} (%) Sample 1	Sample 2	Sample 3
11.5	15	65	56	50
	20	60	55	49
	25	58	50	44
	30	50	46	40
	35	48	42	36
	40	44	40	34
13.0	15	62	51	45
	20	57	50	43
	25	55	45	42
	30	49	42	40
	35	46	41	35
	40	42	39	32
14.0	15	61	50	42
	20	56	48	41
	25	54	45	39
	30	48	42	36
	35	43	39	33
	40	42	36	27
15.0	15	60	48	42
	20	52	46	40
	25	50	43	38
	30	44	40	35
	35	40	36	30
	40	36	33	25
16.0	15	57	46	41
	20	50	44	40
	25	47	40	38
	30	42	36	34
	35	38	34	30
17.0	15	54	44	37
	20	48	42	35

2.2. Fuzzy-Set Theory

Sets are collections of objects with the same properties. In crisp sets, the objects may belong to the set, or may not. In practice, the characteristic value for an object belonging to the set considered is coded as 1 and if it is outside, the set then the coding is 0. In crisp sets, there is no ambiguity or vagueness as to the belonging of each object to the set concerned. On the other hand, in daily life people are always confronted with objects that may be similar to each other with different properties, therefore, there arises uncertainty as to their belonging to a common set with membership values 0 or 1. Of course, logically some of the similar objects may partially belong to the same set. Therefore, an ambiguity emerges in the decision of belonging or not. To alleviate such situations Zadeh [17], generalized the crisp set membership degree as having any value continuously between 0 and 1. The greater the membership degree the more the object belongs to the set.

Any linguistic feature variation can be shown with the fuzzy rules, and represented with general words and fuzzy numbers. For instance, Figure 1 shows a typical membership function for fuzzy subsets of clays' liquid limit values such as "very few", "few", "medium", "high", and "very high". Membership degree and membership function at fuzzy sets are determined by personal intuition, sense, and experience. The triangle, trapezoidal, gaussian, sigmoidal, and $\boldsymbol{\pi}$-shaped membership functions are used in literature. However, the most popular membership functions are triangle and trapezoidal membership functions [20].

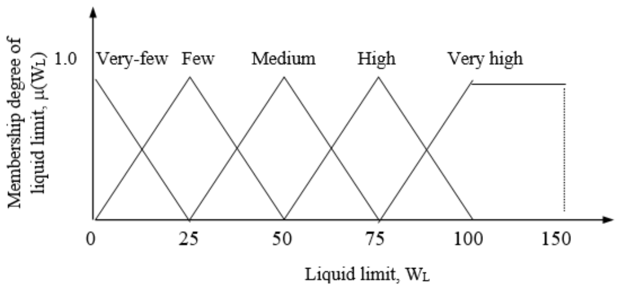

Figure 1. Fuzzy subsets of liquid limit [34]

2.3. Fuzzy Rules

Any solution to uncertainties has three interdependent steps. Successful implementation of these steps leads to a problem's solution in a fuzzy environment, i.e., the solution procedure digests any uncertainty in the basic evolution of the event concerned. The fuzzification step is the first step to the problem's solution with fuzzy rules. It needs to fuzzification the problem and its factors. The inference step systematically relates all factors, pairwise, which take place in the solution depending on the purpose of the problem. This part includes many fuzzy conditional statements to describe a certain situation. For instance, if two events A and B are interactive, then they are dependent on each other. Conditional statements express the dependence verbally, as follows, without any equation as used in the classical approaches,

$$\begin{array}{c} IF\ A\ is\ x(1)THEN\ B\ is\ y(1) \\ ALSO \\ IF\ A\ is\ x(2)THEN\ B\ is\ y(2) \\ ALSO \\ \dots\dots\dots\dots\dots\dots \\ \dots\dots\dots\dots\dots\dots \\ IF\ A\ is\ x(n)THEN\ B\ is\ y(n) \end{array} \qquad (1)$$

where x(.) and y(.) are linguistic descriptions of A and B respectively. The fuzzy conditional statements in Eq. (1) can be formalized in the form of the fuzzy relation R (A, B) as R (A, B) = ALSO (R_1, R_2, R_3, …, R_n), where ALSO is a sentence connection which combines Ri's into the fuzzy relation R (A, B) and Ri denotes the fuzzy relation between A and B determined by the Eq. (1) fuzzy conditional statement. After having the fuzzy relationship R (A, B) the compositional rule of inference is applied to infer the fuzzy subset y for B, given a fuzzy subset x for A as y = x o R (A, B). Where 'o' is the compositional operator [35], [36].

Lots of fuzzy implication relations are used in the literature. Lee [37] pointed out that there are implication relations of more than 40 reported in the literature. Tsoukalas and Uhrig [38] signified that the preference of implication operator depends on sense and intuition. Implication operators used in literature are the following: Zadeh max-min implication operator, Mamdani min implication operator, Larsen product implication operator, Arithmetic implication operator, and Boolean implication operator. In this study, Mamdani's [39] implication operator which is the most popular in fuzzy sets, is preferred due to the most appealing one to employ in engineering problems.

Defuzzification shows the final result from the previous step. The defuzzification method must be applied to calculate the deterministic value of a linguistic variable B. Several defuzzification techniques have been suggested. The most frequently used ones are the centroid or center of area (COA), the center of sums (COS), and the mean of maxima (MOM) [36]. Problem type, problem property, and user opinion affect the choice of the method to be used. The centroid or center of the area (COA) defuzzification technique, which is one of the most common techniques, is applied in this study. In this technique, the crisp suction capacity is taken as the geometric center of the output fuzzy value.

2.4. Why is the Fuzzy-Set Theory Used?

Fuzzy-set theory provides a practicable way to understand and manually influence the mapping behavior. In general, fuzzy logic uses simple rules to describe the system of interest, rather than analytical equations, making it easy to implement [40]. Fuzzy cognitive maps are used as an automated decision aid to assess better how change in one component of a system affects the other components of the same system [41]. If an investigated phenomenon is very confusing and there is no sufficient knowledge, the fuzzy logic method provides a good way to solve problems based on ideas and the standard judgment of a person. In solving engineering problems with the fuzzy logic method, knowing the complexity of a phenomenon is a useful source of information.

In geotechnical engineering, it is generally possible that the results of tests and empirical equations are not in good agreement. Moreover, we watch that the results of the many tests done under, even the same conditions on the same sample, can be similar but not equal. These observations lead us to conclude that tested values scatter in wide spectra. From finite measures, we obtain knowledge about the dimensions of the spectra. But even though we generally know the boundaries of the result of another test within this event, we do not know where it will be placed in the spectra. Thus, this is fuzziness.

According to the Casagrande plasticity card, soils with a liquid limit greater than 50% are called high plasticity soils. But, if we apply fuzzy logic to this card, different degrees of high plasticity can be obtained. For example, if we take a soil with high plasticity as a criterion and compare the other soils with the criterion, soils with lower plasticity can be called low-plasticity soils, and soils with higher plasticity can be called very high-plasticity soils.

3. Results and Discussion

Expert knowledge is the most common technique for determining rules and limit sets. The expert is asked to summarize the knowledge about the system in the form of cause-and-effect relationships, and the rules are formulated. In this study, the factors affecting compacted clays' suction capacity are the plasticity index, water content, and dry density. Any of these factors are considered in fuzzy sets and separated subsets. Literature and results of tests are used to limit these subsets [10], [42], [43], [44].

The dry density, water content, and plasticity index set considered as inputs are divided into the subsets 7, 6, and 10, respectively. In this study, the triangle membership function that is used most in literature is selected. These sets are shown in Figures 2, 3, and 4. The membership functions for dry density, initial water content, and plasticity index fuzzy subsets occurred concerning numbers because many subsets exist. In these figures, $(\boldsymbol{\gamma_d(i)})$, $\boldsymbol{\mu(W_0(j))}$, $\boldsymbol{\mu(PI(k))}$ are membership degrees of dry density, water content, and plasticity index, respectively. $\boldsymbol{\gamma_d(i)}$, $\boldsymbol{W_0(j)}$, and $\boldsymbol{PI(k)}$ are fuzzy subsets of dry density, water content, and plasticity index, respectively. The indexes i, j, and k indicate the number of dry density, water content, and plasticity index fuzzy subsets.

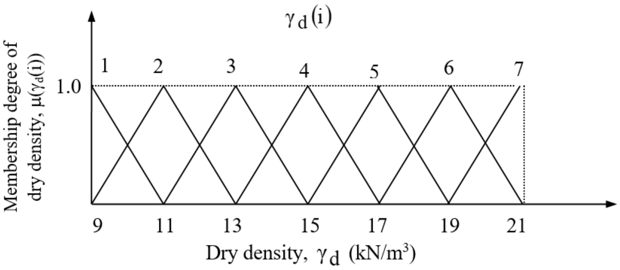

Figure 2. Fuzzy subsets of dry density [34]

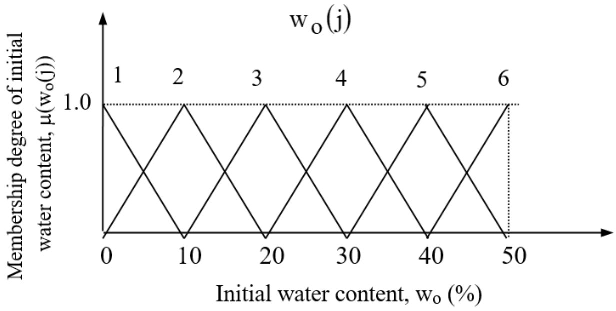

Figure 3. Fuzzy subsets of initial water content [34]

The 14-subset suction capacity set shown in Figure 5 can be obtained as an output If the sets of dry density, initial water content, and plasticity index are taken as input. Here, $\boldsymbol{\mu(W_{suc}(z))}$ is the membership degree for the suction capacity. $\boldsymbol{W_{suc}(z)}$ is the fuzzy subsets of suction capacity and the z index indicates the number of suction capacity subsets The database of subsets is shown in Table 3. As shown in Figure 5, the suction capacity has 14 subsets (5%~400%).

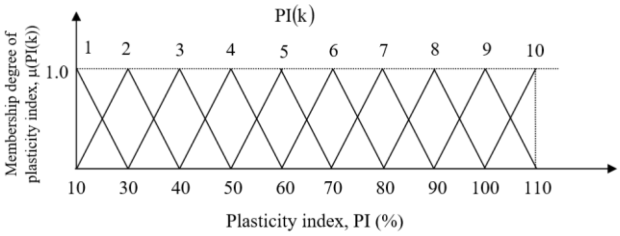

Figure 4. Fuzzy subsets of plasticity index [34]

The rules in Table 3 are formed depending on the results of the suction capacity tests seen in Table 2 and the literature's knowledge. 7x6x10=420 rules are formed for 7 different dry density (9.0kN/m^3~21kN/m^3), 6 different initial water content (0~50%), and 10 different plasticity indexes (10%~110%) fuzzy subsets. For example, for the 1st dry density fuzzy subset (9.0kN/m^3~11kN/m^3) shown in Figure 2, 2rd initial water content fuzzy subset (0~20%) shown in Figure 3, and 3rd plasticity index fuzzy subsets (20%~40%) shown in Figure 4, the predicted suction capacity of the sample consists of number 5 (Wsuc=40%~60%), number 6 (Wsuc=50%~80%), and number 7 (Wsuc=60%~105%) suction capacity fuzzy sets as shown in Figure 5. These rules are written in the Fortran language. Thus, the suction capacity may be predicted depending on compacted clays' dry density, initial water content, and plasticity index. The fuzzy output to estimate suction capacity numerically needs to be fuzzified by a Centroid fuzzification method. The results of the fuzzy logic model are shown in Table 4.

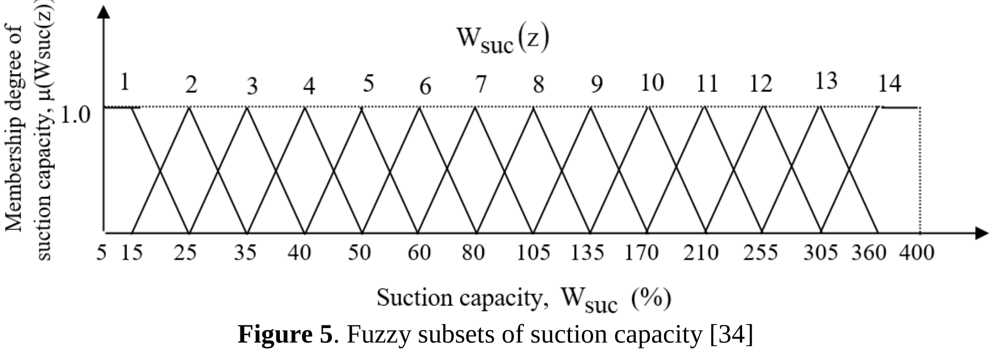

Figure 5. Fuzzy subsets of suction capacity [34]

Table 3. Fuzzy rules to determine the suction capacity [34]

γ_d Subsets number	W_0 Subsets number	PI Subsets number 1	2	3	4	5	6	7	8	9	10
1	1	4-5	5-6	6-7	6-8	7-9	8-10	9-11	10-12	11-13	12-14
	2	3-5	4-6	5-7	6-7	7-8	8-9	9-10	10-11	11-12	12-13
	3	3-4	4-5	5-6	5-7	6-8	7-9	8-10	9-11	10-12	11-13
	4	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12
	5	1-2	2-3	3-4	4-5	5-6	6-8	7-9	8-10	9-11	10-12
	6	1	1-3	2-4	3-5	4-6	6-7	7-8	8-9	9-10	10-11
2	1	3-5	4-6	5-7	5-8	6-9	7-10	8-11	9-12	10-13	11-14
	2	3-4	4-5	5-6	5-7	6-8	7-9	8-10	9-11	10-12	11-13
	3	2-4	3-5	4-6	4-7	5-8	6-9	7-10	8-11	9-12	10-13
	4	1-3	2-4	3-5	4-6	5-7	6-8	7-9	8-10	9-11	10-12
	5	1	1-3	2-4	3-5	4-6	5-8	6-9	7-10	8-11	9-12
	6	1	1-2	1-4	2-5	3-6	5-7	6-8	7-9	8-10	9-11
3	1	2-5	3-6	4-7	4-8	5-9	6-10	7-11	8-12	9-13	10-14
	2	2-4	3-5	4-6	4-7	5-8	6-9	7-10	8-11	9-12	10-13
	3	1-4	2-5	3-6	3-7	4-8	5-9	6-10	7-11	8-12	9-13
	4	1-3	1-4	2-5	3-6	4-7	5-8	6-9	7-10	8-11	9-12
	5	1	1-2	1-4	2-5	3-6	4-8	5-9	6-10	7-11	8-12
	6	1	1	1-3	2-4	3-5	4-7	5-8	6-9	7-10	8-11
4	1	2-4	3-5	4-6	5-7	6-8	7-9	8-10	9-11	10-12	11-13
	2	1-4	2-5	3-6	4-7	5-8	6-9	7-10	8-11	9-12	10-13
	3	1-3	2-4	3-5	4-6	5-7	6-8	7-9	8-10	9-11	10-12
	4	1-2	1-3	2-4	3-5	4-6	5-8	6-9	7-10	8-11	9-12
	5	1	1	1-3	2-4	3-5	5-7	6-8	7-9	8-10	9-11
	6	1	1	1-2	1-4	2-5	4-7	5-8	6-9	7-10	8-11
5	1	1-4	2-5	3-6	4-7	5-8	6-9	7-10	8-11	9-12	10-13
	2	1-4	1-5	2-6	3-7	4-8	5-9	6-10	7-11	8-12	9-13
	3	1-2	1-4	2-5	3-6	4-7	5-8	6-9	7-10	8-11	9-12
	4	1	1-2	1-4	2-5	3-6	4-8	5-9	6-10	7-11	8-12
	5	1	1	1-2	1-4	2-5	4-7	5-8	6-9	7-10	8-11
	6	1	1	1	1-3	1-5	3-7	4-8	5-9	6-10	7-11
6	1	1-3	1-5	2-6	3-7	4-8	5-9	6-10	7-11	8-12	9-13
	2	1-2	1-4	1-6	2-7	3-8	4-9	5-10	6-11	7-12	8-13
	3	1	1-3	1-5	2-6	3-7	4-8	5-9	6-10	7-11	8-12
	4	1	1	1-3	1-5	2-6	3-8	4-9	5-10	6-11	7-12
	5	1	1	1	1-3	1-5	3-7	4-8	5-9	6-10	7-11
	6	1	1	1	1-2	1-4	2-7	3-8	4-9	5-10	6-11
7	1	1-3	2-4	3-5	4-6	5-7	6-8	7-9	8-10	9-11	10-12
	2	1-2	1-4	2-5	3-6	4-7	5-8	6-9	7-10	8-11	9-12
	3	1	1-3	2-4	3-5	4-6	5-7	6-8	7-9	8-10	9-11
	4	1	1	1-3	2-4	3-5	4-7	5-8	6-9	7-10	8-11
	5	1	1	1	1-3	2-4	4-6	5-7	6-8	7-9	8-10
	6	1	1	1	1-2	1-4	3-6	4-7	5-8	6-9	7-10

The results of the fuzzy logic model with three inputs (dry density, initial water content, and plasticity index) and suction capacity tests are compared as shown in Figure 6. It is shown that the results of the fuzzy logic model and experiments are similar. In the prediction of suction capacity, the maximum error is $\pm 10\%$ and the average error is $\pm 2.69\%$.

4. Conclusion and Suggestions

Suction capacity tests done on clayey soil take a long time. The test results of the initial water content, initial dry density, and plasticity index are considered to predict the suction capacity by the fuzzy-set theory in this study. Fuzzy-set theory provides a methodology for describing complex systems using qualitative relationships like quantitative equations such as in geotechnical engineering. A computer program in the Fortran language has been written to estimate the suction capacity of compacted clayey soils using fuzzy sets. The program uses values of dry density, initial water content, and plasticity index fuzzy subsets of compacted soil. A comparison of the results of the experiments and the program that used fuzzy sets was made and a good harmony is obtained between the results of the tests and the results of the fuzzy logic model. Therefore, it is stated that the suggested approach can reliably determine the suction capacity of compacted clayey soils.

Table 4. Results of fuzzy logic model [34]

γ_d (kN/m^3)	W_0 (%)	W^*_{suc} (%) Sample 1	Sample 2	Sample 3
11.5	15	66.2	55.2	50.7
	20	62.7	53.4	49.4
	25	58.8	48.8	43.4
	30	54.2	45.6	38.9
	35	49.3	40.8	35.1
	40	44.0	39.2	33.8
13.0	15	62.0	52.6	45.7
	20	58.6	51.0	44.5
	25	55.2	46.7	41.5
	30	50.8	43.6	39.9
	35	46.3	40.7	34.9
	40	41.0	38.5	33.1
14.0	15	61.1	51.3	43.6
	20	57.6	48.7	41.5
	25	52.9	44.7	38.3
	30	48.3	40.8	35.2
	35	43.8	37.6	32.0
	40	41.2	32.4	27.9
15.0	15	60.3	50.1	41.5
	20	55.3	47.5	40.0
	25	50.6	42.7	35.8
	30	45.0	39.2	33.8
	35	41.2	34.5	29.1
	40	36.7	31.0	23.3
16.0	15	57.8	48.0	39.4
	20	51.6	44.9	37.2
	25	48.5	40.7	36.0
	30	43.4	36.5	31.6
	35	39.1	32.3	27.1
17.0	15	55.2	45.9	37.4
	20	48.8	41.6	35.9

W^*_{suc} (%): Suction capacity obtained by fuzzy logic

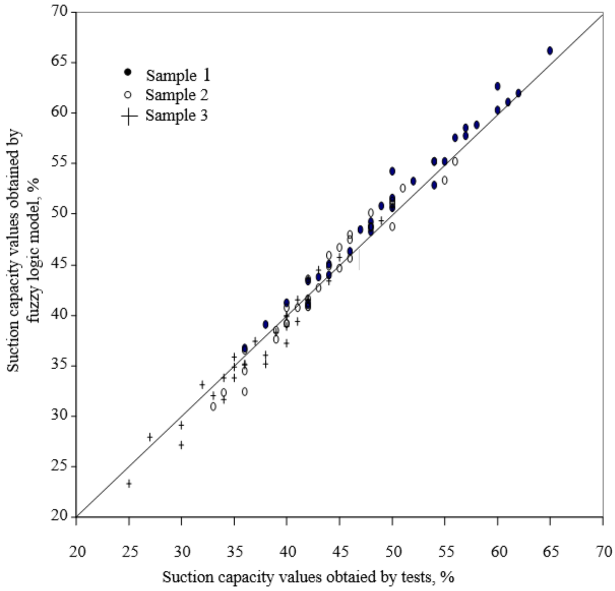

Figure 6. Comparison of the results of fuzzy logic model and tests [34]

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Contributions of the authors

Ömür Çimen: Experiment, Methodology, Conceptualization, Writing-Reviewing and Editing.
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Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics

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