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Neural Network Prediction of Dynamic Characteristics of Soft Soil Disturbance

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Abstract. In recent years, many large-scale projects have been built on thick soft soil foundations. Due to insufficient understanding of the engineering properties of soft soil, many major engineering accidents have occurred. Based on the intersection project of Nangangdao Bridge and subway tunnel in Fuzhou, in order to study the disturbance degree of pile foundation construction to surrounding soil under the influence of multi factor coupling, direct shear test under different disturbance factors (vertical pressure, consolidation time, shear rate, disturbance degree) were carried out on soft soil in Fuzhou, revealing the shear strength characteristics of soft soil in Fuzhou and the sensitivity of peak shear stress to various disturbance factors. The experimental results indicate that all disturbance factors have a significant impact on the stress-strain curve of the soil. As the shear rate increases, the stress-strain curve gradually transitions from strain hardening to strain softening. Propose a sensitivity analysis method to normalize the peak shear stress under various disturbance factors, and obtain the maximum fitting slope of peak shear stress to consolidation time, the highest sensitivity, followed by shear rate, and the minimum disturbance degree. A neural network prediction model for the peak shear strength of saturated soft clay was established using the principle of artificial neural networks. This model has the characteristics of considering multiple factors, high fitting degree, and strong predictive ability.

Keywords. Artificial neural network, dynamic characteristics, degree of disturbance, direct shear test, peak shear stress, saturated soft clay

1. Introduction

With the continuous advancement of urbanization in China, the scale of infrastructure construction in the southeast coastal areas of China is increasing, and a large amount of muddy clay is distributed in the coastal areas. The strength, deformation characteristics, and treatment methods of saturated soft clay have become the primary issues faced in the construction process of coastal areas. This type of soft clay has characteristics such as high water content, high compressibility, large void ratio, low shear strength, and significant rheological deformation. Therefore, soft soil layers in natural state should not be directly used as foundation in infrastructure projects [1-2].Therefore, it is particularly important to understand the strength and deformation characteristics of soft soil layers under different natural conditions. In order to meet the requirements for the strength and deformation of foundation and subgrade, it is also possible to reinforce natural soft soil layers [3-5]. In the process of pile foundation construction, various

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factors have a significant impact on the shear strength of soft soil foundation. There is relatively little research on the achievements in this area, so it is necessary to study the relationship between the disturbance conditions during the construction process and the changes in soft soil strength.

In the research of geotechnical constitutive relations, there are more and more models with complex expression forms, but there are some drawbacks in the application in practical engineering. In practical engineering, engineers mainly focus on the actual response characteristics and practicality of working conditions, rather than the parameters and expression forms of constitutive models. Artificial neural networks (ANNs) have strong advantages in dealing with such problems, and incorporate practical forces into the study of constitutive models in geotechnical engineering [8-9].

Among the forms of soil failure, there are soil cracking due to excessive tensile force, as well as damage due to excessive shear force. In most engineering problems, such as soil slope stability issues, foundation bearing capacity issues, soil disturbance damage issues, foundation pit excavation soil deformation and safety and stability issues, shear strength of soil is mainly considered. There are many factors influencing the shear strength of soil, and they are also very complex. According to the sensitivity analysis method proposed by Mohammadizadeh, SM [10], it is of great significance to study the sensitivity of various influencing factors to the strength characteristics of saturated soft clay, which can provide important theoretical support for geotechnical engineering design and safety and stability prediction analysis.

2. Sample Preparation and Testing Details

2.1. Description of the Tested Soil

The soil for the test was taken from the middle section of the bottom plate elevation of the subway tunnel roof at the intersection of the Nangang Road Bridge on Fuzhou New City Expressway and the Metro Line 6 tunnel, with a depth of 5-19m. A thin-walled soil sampler was used to penetrate the soil sample, and the soil sample grade was Grade I. After sampling, all joints were sealed with adhesive tape, wrapped with plastic wrap to prevent the evaporation of the original soil moisture, and packaged with wooden boxes for centralized shockproof packaging. The soil sample belongs to the typical marine sedimentary soft soil in Fuzhou area.

Basic physical tests shall be conducted to determine the natural weight of the undisturbed soil. The alcohol combustion method shall be used to repeatedly determine the natural water content of the undisturbed soil samples. The specific gravity of the soil particles shall be determined using the pyknometer method, and the limit water content shall be determined using the liquid plastic limit combined measurement method. The basic physical indicators are shown in Tab. 1 below.

Table 1. Basic Physical Indexes of Undisturbed Soil.

Natural soil weight γ/kN*m^{-3}	Natural water content w/%	Proportion Gs	Liquid limit w_L/%	Plastic limit w_p/%	Plasticity index I_p
17.97	33.6	2.70	65.6	24.6	41.0

The undisturbed soil sample used in the test is a fine grained soil that is not easily permeable to water. Using the vacuum saturation method, the undisturbed soil sample with a ring knife is placed in a saturator, and then placed in a vacuum cylinder for air extraction saturation. The standing time is set to 12 hours to fully saturate the undisturbed soil sample.

The remolded soil sample used in the test is the undisturbed soil sample that has been fully air dried, removed impurities, hammered and crushed through a 0.45mm geotechnical sieve, and repeatedly measured the moisture content after air drying. A remolded soil sample with the same dry density and moisture content is prepared using the sample pressing method based on the volume of the ring knife and the dry density and moisture content of the undisturbed soil, and then the remolded soil sample is fully saturated.

The artificially prepared structural soil samples with different disturbance levels used in the test are prepared from 1% and 2% cement soil samples, using remolded soil that has passed a 0.45mm geotechnical sieve, cement with a model of 525 Portland, edible salt, and water as materials. Adding cement to the remolded soil can establish a bond between soil particles, and the dissolved edible salt in the remolded soil can construct the macropore characteristics of soft clay, The specific preparation method is as follows:

(1) After fully mixing and mixing the mixture described above, place it in a ring knife, compact it using a sample pressing method, add an appropriate amount of water, and place it in a humid environment to achieve initial setting.

(2) Place the soil sample in flowing water for 1 day, dissolve all the edible salt particles and take them away with the water flow.

(3) Saturate the sample by air extraction, and cure all samples for 3 days before conducting the test.

The proportion of manually prepared structural soil is shown in Table 2.

Table 2. Proportions of Manually Prepared Structural Soil.

Artificial structural soil	**S_m/%**	**C_m/%**	**Edible salt/g**
$C_{1.0}$	99	1	8
$C_{2.0}$	98	2	8

Note: S_m is the ratio of clay mass to the total mass of clay and cement; C_m is the ratio of the mass of cement to the total mass of clay and cement.

2.2. Test Plan

There are four groups of undisturbed soil samples and remolded soil samples each,the test plan is shown in the table below.

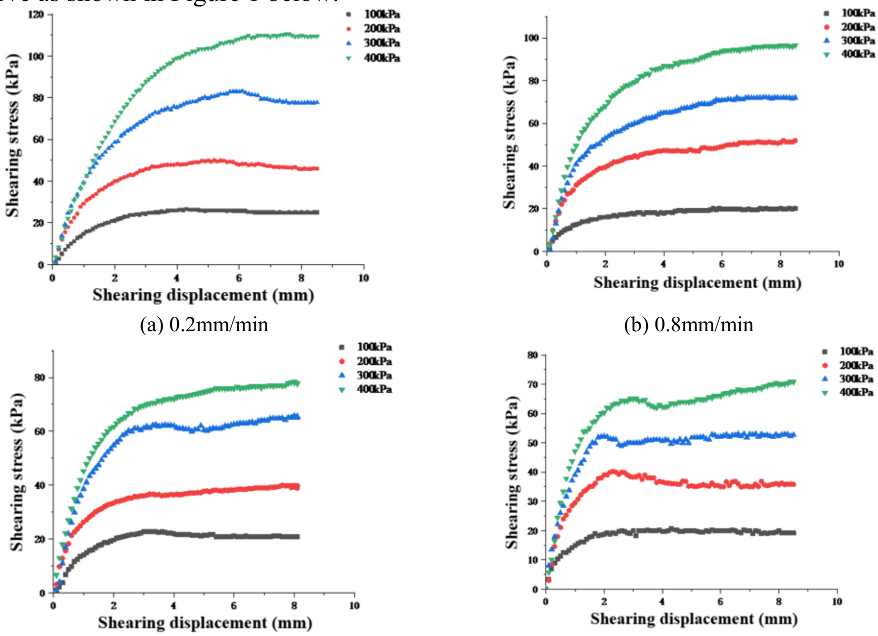
Tab.3 Direct Shear Test Plan

	Degree of sample disturbance	**Shear rate (mm/min)**	**Consolidation time (min)**	**Vertical pressure (kPa)**
Undisturbed sample	Undisturbed	0.2, 0.8, 1.6, 2.4	100	100, 200, 300, 400
Disturbed sample	Remodeling	0.2, 0.8, 1.6, 2.4	100	100, 200, 300, 400
	Reconsolidation	0.8	5, 40, 100	100, 200, 300, 400
	Artificial structural soil (1%, 2% cement soil)	0.8	100	100, 200, 300, 400

3. Analysis and Discussion of Test Results

3.1. Strength Characteristics of Undisturbed Specimens

For undisturbed soil samples with basically the same physical properties, measure the shear displacement and shear stress at the shear rates of 0.2mm/min, 0.8mm/min, 1.6mm/min, and 2.4mm/min, and draw the shear displacement shear stress relationship curve as shown in Figure 1 below.



(a) 0.2mm/min (b) 0.8mm/min

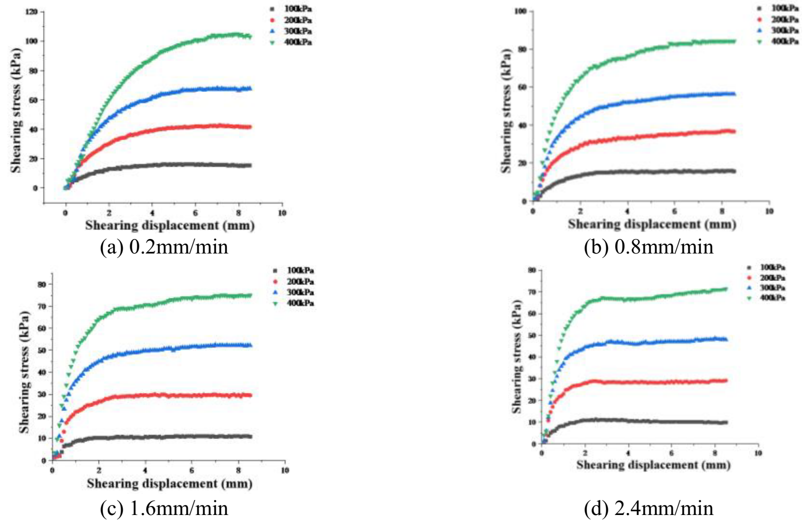
(c) 1.6mm/min (d) 2.4mm/min

Figure 1. Shear displacement shear stress curve of undisturbed soil.

3.2. Strength Attenuation Characteristics of Disturbed Soil

- Strength characteristics of remolded soil

For remolded soil samples with basically the same physical properties, measure the shear displacement and shear stress at the shear rates of 0.2mm/min, 0.8mm/min, 1.6mm/min, and 2.4mm/min, and draw the shear displacement shear stress relationship curve as shown in Figure 2 below.



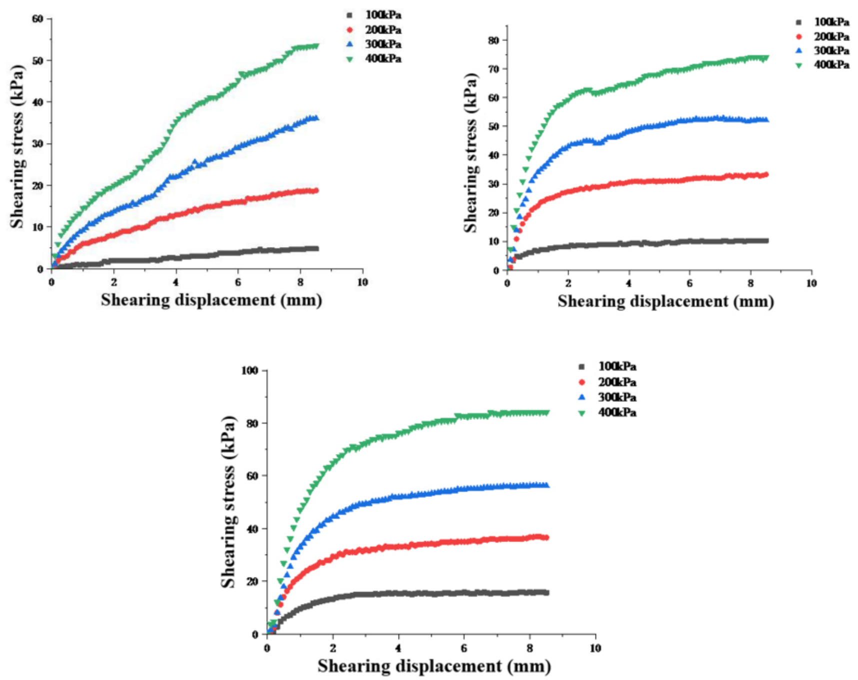
(a) 0.2mm/min (b) 0.8mm/min

(c) 1.6mm/min (d) 2.4mm/min

Figure 2. Shear displacement shear stress curve of remolded soil.

- Strength characteristics of reconsolidated soil

For remolded soil samples with basically the same physical properties, measure the shear displacement and shear stress at a shear rate of 0.8mm/min after the consolidation time of 5min, 40min, and 100min, and draw the shear displacement shear stress relationship curve as shown in Figure 3 below.



(a) 5min (b) 40min (c) 100min

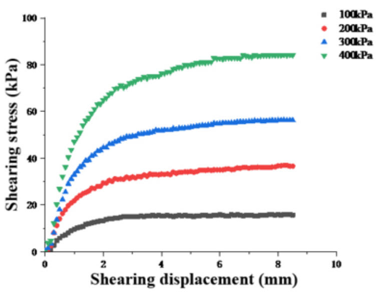
Figure 3. Shear displacement shear stress curve of remolded soil at different consolidation times.

- Strength characteristics of soils with different degrees of disturbance

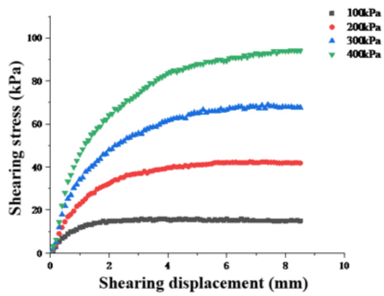
For artificial structural soil samples with basically the same physical properties and cement parameters of 1% and 2%, respectively measure the shear displacement and shear stress at a shear rate of 0.8mm/min, and draw the shear displacement shear stress relationship curve as shown in Figure 4 below.

The test results show that vertical pressure, shear rate, consolidation time (degree of consolidation), and degree of disturbance all affect the shear displacement and shear stress curve of soil. The higher the vertical pressure, the greater the peak shear stress; the higher the shear rate, the smaller the peak shear stress; the greater the peak shear stress; the greater the soil disturbance, the smaller the peak shear stress.

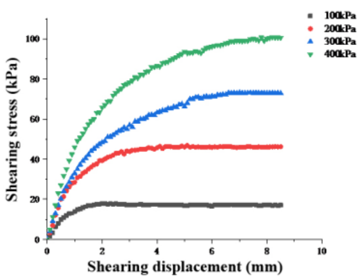
The degree of consolidation has the most significant effect on the peak shear stress in the shear displacement and shear stress curves. The shear displacement and shear stress curves of undisturbed and remolded soils gradually show a trend of strain softening with the increase of shear rate.



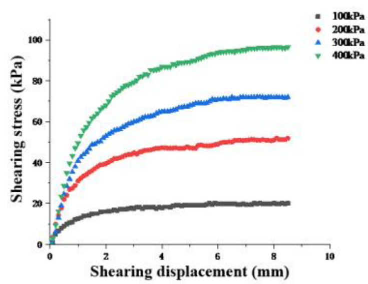
(a)Remolded soil



(b)1% cement soil



(c)2% cement soil



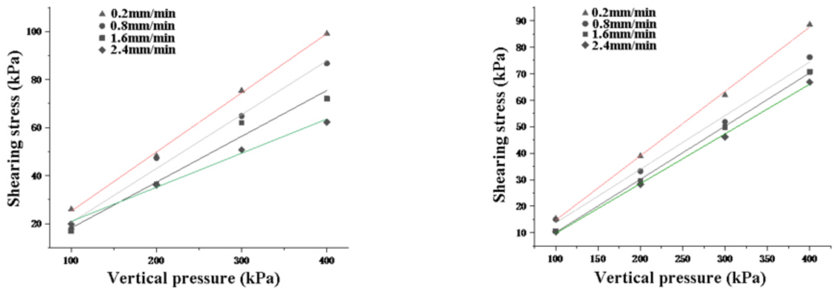
(d)Undisturbed soil

Figure 4. shear displacement shear stress curves of soils with different disturbances.

3.3. Study on the Influence of Various Factors on the Peak Shear Stress

- Effect of shear rate on peak shear stress

According to the shear displacement and shear stress test curves of undisturbed soil and remolded soil at the shear rates of 0.2mm/min, 0.8mm/min, 1.6mm/min, and 2.4mm/min, respectively, take the shear displacement Δ the shear stress corresponding to L=4mm is taken as the shear strength S and is the peak shear stress. The relationship between the peak shear stress and vertical pressure for undisturbed soil and remolded soil at different shear rates is shown in Figure 5 and 6.



(a) Remolded soil (b) Undisturbed soil

Figure 5. Relationship curve between peak shear stress and vertical pressure under different shear rates.

As can be seen from Figure 5, with the increase of shear rate, the peak shear stress under each vertical pressure presents a decreasing trend. When the vertical pressure of undisturbed soil and remolded soil is lower than that of 100kPa or 200kPa, the difference between the peak shear stress under each shear rate is small. When the vertical pressure of 100kPa is applied to undisturbed soil, the shear rate is large but the peak shear stress is also large. This phenomenon indicates that with the increase of vertical pressure, The effect of shear rate on peak shear stress is more obvious.

- Effect of consolidation time on peak shear stress

According to the direct shear test of remolded soil at a shear rate of 0.8mm/min under a consolidation time of 5min, 40min, and 100min, the relationship curve between the peak shear stress and vertical pressure is shown in Figure 6 below.

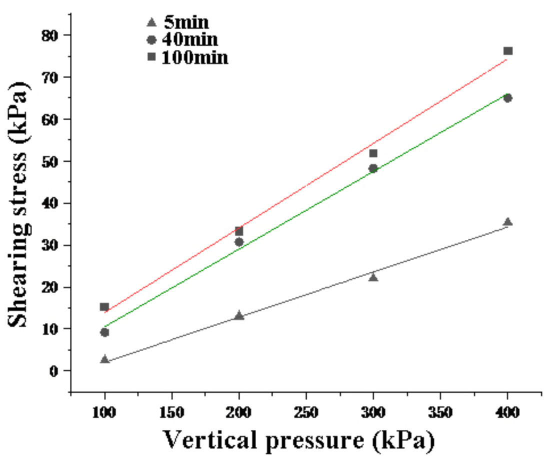


Figure 6. Relationship curve between peak shear stress and vertical pressure of remolded soil at different consolidation times.

As can be seen from Figure 6, with the increase of vertical pressure, the peak shear stress increases linearly. Under the same vertical pressure, the longer the consolidation time, the greater the peak shear stress. The peak shear stress increases most significantly during the consolidation time of 5 to 40 minutes, and the peak shear stress increases slowly during the consolidation time of 40 to 100 minutes. This phenomenon occurs because the main consolidation of soft clay is mostly completed within 40 to 100 minutes, With the discharge of pore water from soft clay, the effective stress of the soil gradually increases, and the peak shear stress increases significantly. After the primary consolidation of soft clay is completed, it enters the secondary consolidation stage, where pore water almost no longer discharges, soil particles undergo creep and adjustment, and the effective stress between soil particles increases slowly, and the peak shear stress slightly increases during the consolidation time of 40 to 100 minutes; The slope of the fitting curve increases as the consolidation time increases within the range of 5 to 100 minutes.

- The effect of disturbance on the peak shear stress

According to the prepared artificial structural soil samples with different cement content, direct shear tests of the soil were conducted at the same consolidation time and shear rate. The relationship curve between the peak shear stress and vertical pressure is shown in Figure 7 below.

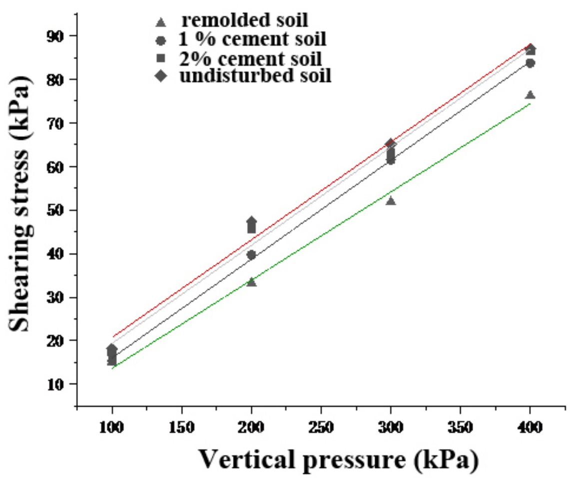


Figure 7. Shear Stress Peak and Vertical Pressure Relationship Curves with Different Disturbances.

As can be seen from Figure 7, under the same vertical pressure, the greater the degree of disturbance, the smaller the peak shear stress. The order of the peak shear stress is: undisturbed soil, 2% cement-soil, 1% cement-soil, remolded soil. Artificial structured soil has a better effect in simulating soft clay with different degrees of disturbance.

3.4. Sensitivity Discussion of Various Factors Affecting Peak Shear Stress

According to the research in section 2.3, the magnitude of peak shear stress is mainly related to shear rate, consolidation time, and degree of disturbance. In the range of shear rate from 0.2 to 2.4 mm/min, the reference is 2.4 mm/min, the reference is 100 min for the range of consolidation time from 5 to 100 min, and the reference is undisturbed soil; The variation degree of peak shear stress under various influencing factors is shown in the table below.

Table 4. Percentage of peak shear stress of undisturbed soil under various vertical pressures based on a shear rate of 2.4mm/min.

Shear rate /mmmin^{-1}	Percentage /%	Percentage at different vertical pressures /%			
		100kPa	**200kPa**	**300kPa**	**400kPa**
0.2	8	131	133	155	160
0.8	33	92	130	131	139
1.6	67	89	101	128	117
2.4	100	100	100	100	100

Table 5 Percentage of peak shear stress of remolded soil under various vertical pressures based on a shear rate of 2.4mm/min.

Shear rate /mmmin^{-1}	Percentage /%	Percentage at different vertical pressures /%			
		100kPa	**200kPa**	**300kPa**	**400kPa**
0.2	8	149	140	137	142
0.8	33	147	116	113	116
1.6	67	102	104	109	106
2.4	100	100	100	100	100

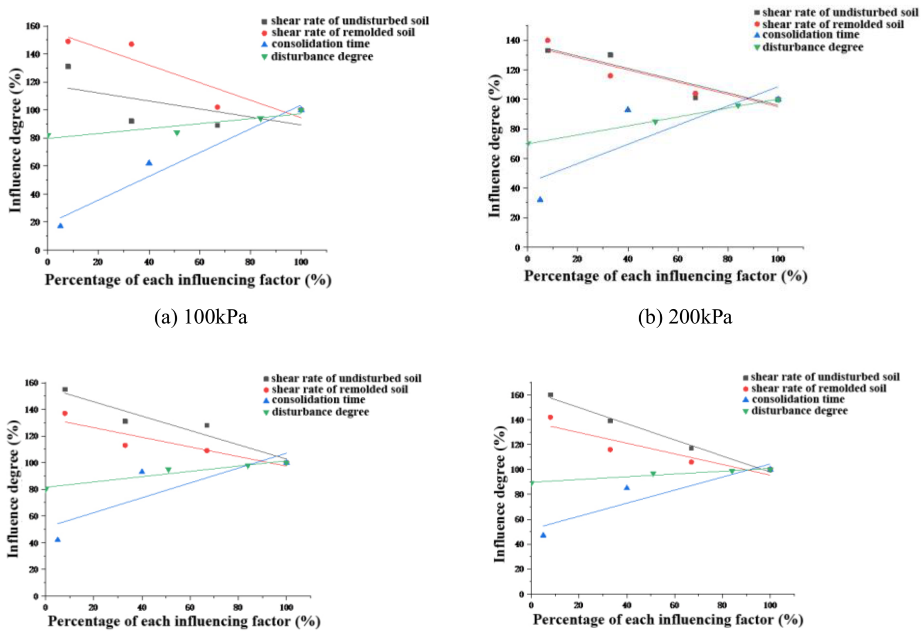
Table 6. Percentage of peak shear stress and vertical pressure of remolded soil based on consolidation time of 100min.

Consolidation time /min	Percentage /%	Percentage at different vertical pressures /%			
		100kPa	**200kPa**	**300kPa**	**400kPa**
5	5	17	32	42	47
40	40	62	93	93	85
100	100	100	100	100	100

Table 7. Percentage of peak shear stress per vertical pressure based on different perturbation degrees.

Disturbance degree	Percentage /%	Percentage at different vertical pressures /%			
		100kPa	**200kPa**	**300kPa**	**400kPa**
Remolded soil	0	82	70	80	89
1% cement soil	51	84	85	95	97
2% cement soil	84	94	96	98	99
Undisturbed soil	100	100	100	100	100

In the table above, the influence degree of each influencing factor on the peak shear stress varies. In order to explore the sensitivity of the magnitude of the peak shear stress to the shear rate, consolidation time, and degree of disturbance, the percentage of each influencing factor and the influence degree curve of the peak shear stress are calculated at 100kPa, 200kPa, 300kPa, and 400kPa, respectively:



(a) 100kPa (b) 200kPa

(a) 300kPa (b) 400kPa

Figure 8. Curve of percentage of each influencing factor and influence degree of peak shear stress.

From the above Figure 8, it can be seen that the absolute value of the slope of the fitting line for consolidation time is the highest, followed by the absolute value of the slope of the fitting line for shear rate, and the absolute value of the disturbance fitting line is the lowest. This indicates that in direct shear tests of soil, the sensitivity of peak shear stress to consolidation time is the highest, followed by shear rate, and the sensitivity of disturbance is the lowest.

As the consolidation time increases, the degree of consolidation of soft soil increases, and the soil particles change significantly. The arrangement and distribution of particles gradually become tight, and the pores are gradually filled with broken small particles. The effective stress between soil particles gradually increases, leading to a gradual increase in soil strength. Compared to the consolidation time, the degree of disturbance in the soil is less sensitive to it. In the soil disturbance process described in the article, soil samples with different cement dosages indicate different particle arrangements and cementation effects. The sensitivity analysis results indicate that the shear resistance of soil is most significantly affected by effective stress.

4. 3 Neural Network Prediction Model for Strength of Saturated Soft Clay

In order to study the feasibility of using neural networks to establish the stress and strain of saturated soft clay and the impact of input variables and training samples on the performance of the model, different combinations of input variables and training samples were selected to establish a neural network prediction model for the peak shear stress of soft clay, namely Model A. Model A establishes a neural network model for nonlinear stress-strain curves of soft soil based on the results of direct shear tests under conditions such as multiple degrees of disturbance, multiple vertical stresses, and multiple shear rates for the same soil, peak shear strength τ as an output variable (Figure 9-a). The neural network model is expressed as follows:

$$\tau = f\left(\sigma_v, t, v, D\right)$$

Where, σ_v is the vertical stress, t is the consolidation time, v is the shear rate, and D is the degree of disturbance.

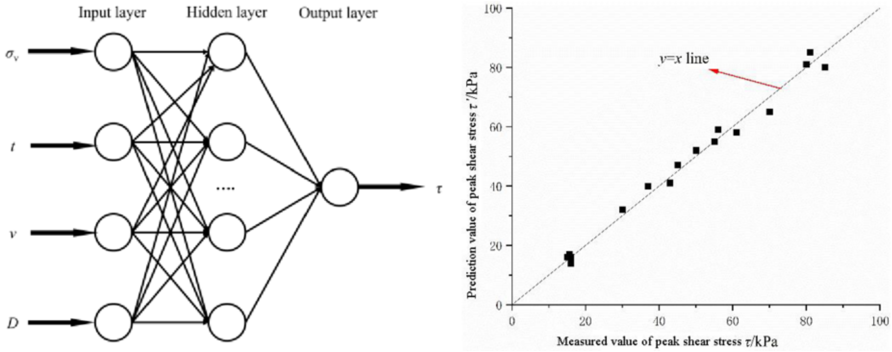


Figure 9. a) Structure of Soft Soil Neural Network Constitutive Model; b) Comparison of predicted and measured peak shear stresses in saturated soft clay under different disturbance levels

Using Matlab's neural network toolbox for programming operations. with σ_v,t,v,D are used as the inputs of the network, and shear stress is used as the output of the network. A neural network model is established. The structure of the BP neural network model is 5-13-1. The network is trained using the results of direct shear tests. Taking the peak shear stress of soft soil under different disturbance levels as an example, the predicted value and the measured value are shown in Figure 9-b. The two values are uniformly distributed on both sides of the y=x line, and the values are basically consistent.

5. Conclusion

In this paper, the undisturbed soil taken from the intersection of Fuzhou Nangangdao Bridge and subway tunnel is taken as the test object, and the strength and deformation characteristics of saturated soft clay under different disturbance factors (vertical stress, shear rate, disturbance degree, consolidation time) are analyzed by using strain controlled direct shear apparatus. A prediction model for peak shear stress under different disturbance factors was established based on artificial neural networks.

(1) The various disturbance factors in this article have varying degrees of influence on the shear displacement and shear stress curves of saturated soft clay, with consolidation time having the most significant impact on the curves. The shear displacement and shear stress curves of undisturbed and remolded soils gradually change from strain hardening to strain softening with the increase of shear rate.

(2) The concept of sensitivity analysis was proposed, and the sensitivity of peak shear stress to different disturbance factors was compared. Its sensitivity to consolidation time was the highest, followed by shear rate and disturbance degree.

(3) Based on artificial neural networks, a prediction model for peak shear stress was established, which can effectively predict and analyze the peak shear stress under the influence of various factors in the text.

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