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Study of pile shaft resistance in clayey soils

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Abstract: Based on principal component analysis, the rules of clayey soil's behaviors affected by varied indices are studied. It is discovered that the common method of the single liquidity index I_L used to determine the consistency of silt-clay or silt-loam is not rational. It is more rational that the liquidity index I_L combined with the void ratio e characterizes the behavior of silt-clay. Similarly the index of e depicts the nature of sandy loam more rationally than I_L. The method of predicting the pile shaft resistance by the two indices of e and I_L, which is more accurate, is obtained by the methodology of back propagation (BP) artificial neural networks combined with principal component analysis. It is also observed that the pile shaft resistance increases with the increase of depth within a critical affect-depth ranging from 20 to 30 m, and the harder the clayey soil consistency is, the shallower the critical depth is.

Key words: large diameter bored piles; principal component analysis; artificial neural networks; pile shaft resistance

The ultimate bearing capacity of a single pile derived from the external stability analysis is one of the most widely used approaches in pile foundations, in which the shear strength between the pile shaft and its boundary soil is used. The shaft resistance of large diameter bored piles (LDBPs) in clayey soils was investigated by static load tests of the instrument piles with stress measurement in bridge engineering[1].

For the investigation and design of pile foundations in bridge engineering, the criterion DBC[2] gives fundamental regulations. DBC is the short form for "Specifications for Design of Ground Base and Highway Bridge and Culverts" (JTJ 024—85) in this paper. Plasticity index I_P is used to classify clayey soils as shown in Tab. 1. Liquidity index I_L is used for determination of the clayey soils' consistency as shown in Tab.2. In the code DBC, the ultimate pile shaft resistance is determined by the following steps: ① Classify the soils as Tab.1; ② Get the consistency as Tab.2; ③ Get the pile shaft resistance f_s by the classification and consistency.

For division of clayey soils' consistency, the liquidity index I_L as a laboratory index can reflect the behavior of clayey soils to some degree, but this judgement does not coincide with mechanics property in some instances. In this paper, the physical parameters of saturated clayey soils are investigated by principal component analysis (PCA) and the correlation between physical property and mechanical characteristics is discussed. Finally conclusions are given.

Tab.1 Classification of clayey soils

Cohesive soil	Plasticity index I_P
Clay	$I_P > 17$
Silt-clay	$7 < I_P \leq 17$
Sandy loam	$1 < I_P \leq 7$

Tab.2 Relative consistency of clayey soils

Consistency	Plasticity index I_L
Hard or quasi-hard	$I_L < 0$
Hard-plasticity	$0.0 \leq I_L < 0.5$
Soft-plasticity	$0.5 \leq I_L < 1.0$
Liquidity	$I_L \geq 1.0$

1 Mathematical Analysis for Clayey Soil Consistency

1.1 Principal component analysis

Principal component analysis[3] is a multivariate procedure which can be utilized to transform a number of possibly correlated variables into a smaller number of uncorrelated variables called principal components. The main use of PCA is to discover or reduce the dimensionality of the data set and identify new meaningful underlying variables. The first principal component, which is typically the most important, accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible, and they are all independent of each other.

In this paper, ten physical property indices of clayey soil reflecting its property information are researched by PCA. The data sets of original variables

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are chosen from an engineering geologic investigation report of Xicheng Freeway and Xiyi Freeway in Jiangsu province. The eigenvector of the first principal component and its contribution are given in Tab.3, and the correlative coefficients of the primary indices for clayey soils are given in Tab.4.

Tab.3 Eigenvector and variance contribution ratio of the first principal component

Classification	$x_1(z)$	$x_2(w)$	$x_3(\rho)$	$x_4(d_s)$	$x_5(e)$	$x_6(S_r)$	$x_7(W_L)$	$x_8(W_P)$	$x_9(I_P)$	$x_{10}(I_L)$	Contribute ratio/%
Clay	0.02	0.48	-0.50	-0.09	0.49	-0.06	-0.11	-0.07	-0.08	0.49	38.15
Silt-clay	-0.07	0.47	-0.46	0.28	0.48	-0.05	0.25	0.22	0.05	0.37	42.57
Sandy loam	-0.15	0.45	-0.43	0.10	0.45	0.04	0.40	0.37	0.25	0.15	44.71

Tab.4 Correlation coefficients of primary indices

Indices	Clay				Silt-clay				Sandy loam			
	x_2	x_3	x_5	x_{10}	x_2	x_3	x_5	x_{10}	x_2	x_3	x_5	x_7
x_2	1.00	-0.95	0.98	0.84	1.00	-0.95	0.99	0.83	1.00	-0.92	0.98	0.62
x_3	-0.95	1.00	-0.98	-0.89	-0.95	1.00	-0.98	-0.80	-0.92	1.00	-0.97	-0.67
x_5	0.98	-0.98	1.00	0.85	0.99	-0.98	1.00	0.81	0.98	-0.97	1.00	0.66
x_{10}	0.84	-0.89	0.85	1.00	0.83	-0.80	0.81	1.00	0.62	-0.67	0.66	1.00

The contribution ratio of the first principal component for clay is 38.15%, and the absolute values of the weight-coefficients of water content w, natural density ρ, void ratio e and liquidity index I_L are 0.48, 0.50, 0.49, 0.49, respectively, which are much higher than other indices. So the clay property is mainly affected by w, ρ, e and I_L comprehensively. Without exception, the coefficients among e, w and ρ in correlation matrix for clay account for more than 0.98 and the correlation coefficient between e and I_L is 0.85. Therefore it is more rational to adopt two indices (e and I_L) for explaining the physical property of clay. On the other hand, considering the consistency affected by the interaction between clayey particle and water, I_L as the index used to classify the consistency of clay is basically practical.

The contribution ratio of the first principal component of silt-clay is 42.57%, and the weight-coefficients of w, ρ, e and I_L are 0.47, 0.46, 0.48 and 0.37, respectively, and still much higher than other indices. But it is not rational that the index I_L is used to classify the consistency of sandy loam, for the weight-factor of I_L is merely 0.15 in the first principal component. The weight-coefficient of e for silt loam is up to 0.45 in the first principal component, so the void rate e is utilized to classify the consistency more rationally.

1.2 Discussion on consistency of clayey soils

Furthermore the correlation between the physical property index and the mechanical index of clayey soils was investigated by classical correlative analysis. Based on the results from PCA, $w(a_1)$, $e(a_2)$, $w_L(a_3)$, $I_L(a_4)$ are selected as the first group variables; $a_{1-2}(b_1)$, $\beta(b_2)$, SPT(b_3) as the second group variables, and β formulated by the plastic theory of foundation bearing capacity of L. Prandlt (1920), is a synthesis of undrained cohesion c_u and friction angle ϕ_u. That is

$$\beta = \left[c_u \left(e^{\pi \mathrm{tg} \varphi_u} \tan^2 \left(45° + \frac{\varphi_u}{2} \right) - 1 \right) \tan^{-1} \varphi_u \right]^{0.5}$$

The weight-factor a_2 is the maximum (0.808 to 0.976), which increases with the decrease of plasticity of clayey soils as shown in Tab.5. It proves the effectiveness of index e as a judgement for cohesive soil again. By the same principle, the weight-factor of I_L is 0.251, which indicates the feasibility of I_L as a

Tab.5 Summary of representative correlation analysis

Classification		χ^2 test				The first group				The second group		
		Correlation coefficient	χ^2 value	Degree of freedom	Significant level	a_1	a_2	a_3	a_4	b_1	b_2	b_3
Clay	Maximum	0.946	45.127	12	0.000	-0.529	0.808	-0.073	0.251	0.510	-0.675	-0.534
	Second	0.457	4.202	6	0.650	-0.734	0.475	0.432	0.223	0.416	-0.251	0.874
	Third	0.114	0.210	2	0.900	0.030	-0.714	0.261	0.645	0.703	0.711	-0.036
Silt-clay	Maximum	0.899	45.640	12	0.000	-0.126	0.895	-0.039	-0.182	0.270	-0.747	-0.607
	Second	0.491	7.315	6	0.293	-0.775	0.286	0.336	0.453	0.264	0.789	-0.555
	Third	0.236	1.200	2	0.459	0.310	0.470	-0.384	-0.732	0.811	0.236	0.536
Sandy loam	Maximum	0.850	22.403	12	0.033	-0.121	0.976	-0.019	-0.178	0.253	0.569	-0.782
	Second	0.506	5.326	6	0.503	-0.660	0.738	-0.090	-0.115	0.294	0.950	-0.115
	Third	0.371	1.629	2	0.443	-0.790	0.356	0.295	0.403	0.568	-0.383	0.728

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judgement for clay. As for silt-clay, the first classical variable is more important, and the weight-factor of I_L loses its position, and for sandy loam it is totally implausible. So it is reasonable to adopt I_L as the classification of consistency for clay, and it will be more effective if combined with index e for silt-clay. For sandy loam with low plasticity, void ratio e seems much better.

For soil mechanical indices, the clay's weight-factors of a_{1-2}, β and SPT-N in the maximum variable of classical correlative analysis are approximately the same. But the weight-factor of β and SPT-N increase obviously for silt-clay. For sandy loam, the correlation between SPT-N and its physical property is maximal. In other words, SPT-N is the best method to reflect the physical property of sandy loam, and can be utilized to determine other parameters indirectly. Besides, index β has a good correlation with its physical property for clay and silt-clay.

From the above results it is clearly observed that there are problems in classifying consistency by single index I_L for clayey soils named as DBC. The stronger the plasticity of clayey soil, the greater the influence of index I_L. Contrarily, the effect of compactness increases with the decrease of plasticity. So it is better to use both e and I_L than to use a single index I_L to classify consistency of saturated clayey soil.

2 Prediction of Pile Shaft Resistance in Saturated Clayey Soils

A total [4] of 10 instrumented bored piles equipped with sensors for bridge foundation in history cases of Xiceng Freeway and Xiyi Freeway in Jiangsu province were searched for studying the pile shaft resistance. During loading in the static load test, the stress along the pile shaft was measured simultaneously.

The pile shaft resistance measured in sandy loam is insufficient, only five groups are available as shown in Tab.6. Nevertheless, the measurements support the proposition that pile shaft resistance is not related to consistency determined by liquidity index I_L, and also proves that void ratio e and f_s have better correlativity than I_L for low plasticity sandy loam. But the data are insufficient in sandy loam.

Tab.6 Test values of skin resistance in sandy loam

z/m	f_s/kPa	e	I_L
11.50	64.00	0.83	0.49
29.25	40.57	1.02	0.99
6.60	66.61	0.86	1.23
8.85	64.00	0.86	1.23
33.36	82.00	0.78	1.55

The pile shaft resistance measured in silt-clay is given in Tab.7. The relationship between testing pile shaft resistance and void ratio, and liquidity index I_L are shown in Fig. 1 and Fig. 2. The relationship between the void ratio and the pile shaft resistance measured in field is better than that of the liquidity index I_L and the pile shaft resistance. So it is more reasonable to use both e and I_L to predict pile shaft resistance in silt-clay.

In order to consider void ratio e and liquidity index I_L comprehensively, the BP neural networks method is applied. The data sets are used as a study sample in Tab. 7. BP model with two input nodes predicts the ultimate pile shaft resistance, then the results by two indices (e and I_L) can be obtained, as shown in Tab.8. It indicates that the prediction with both e and I_L is much more accurate than that by single I_L for ultimate pile shaft resistance of silt clay.

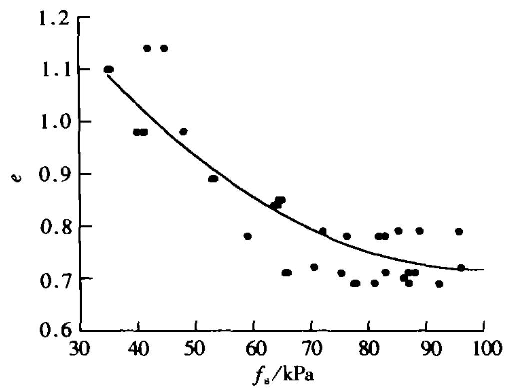

Fig.1 Correlation of friction and void ratio

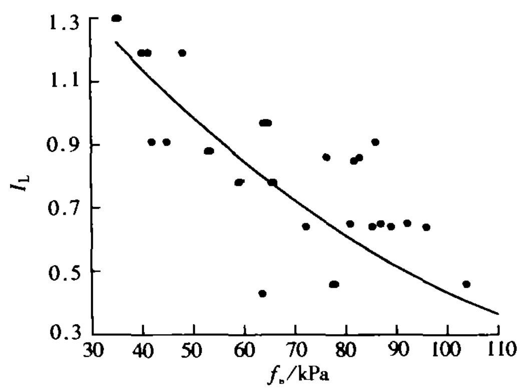

Fig.2 Correlation of friction and liquidity index

3 Mechanism of Pile Shaft Resistance in Saturated Clayey Soils

In the sand, pile shaft resistance affected by depth has been explained by the arching effect and some relative computation method is provided by test data. However, very little has been done on the piles in clayey soils.

Tab.7 Test values of pile skin resistance in silt-clay

z/m	f_s/kPa	e	I_L	z/m	f_s/kPa	e	I_L	z/m	f_s/kPa	e	I_L
1.50	35.44	0.98	0.86	24.11	118.99	0.72	0.27	5.00	83.00	0.71	0.22
5.45	41.25	0.98	1.19	28.23	124.32	0.72	0.27	7.10	35.00	1.10	1.30
10.30	48.07	0.98	1.19	31.88	96.10	0.72	0.27	9.35	65.00	0.85	0.97
15.25	39.95	0.98	1.19	35.15	70.58	0.72	0.27	16.75	42.00	1.14	0.91
20.00	44.91	1.14	0.91	5.70	64.46	0.85	0.97	17.90	78.00	0.69	0.46
24.67	86.11	1.14	0.91	14.40	64.33	0.84	0.97	18.15	59.00	0.78	0.78
29.42	95.90	0.79	0.64	21.75	81.89	0.78	1.55	24.40	87.00	0.69	0.65
33.67	85.31	0.79	0.64	7.05	35.53	1.10	1.30	29.00	64.00	0.84	0.97
37.24	72.24	0.79	0.64	17.60	59.11	0.78	0.78	29.95	53.00	0.89	0.88
1.30	75.29	0.71	0.22	30.20	53.48	0.89	0.88	30.00	101.00	0.72	0.27
4.00	88.10	0.71	0.22	18.20	81.03	0.69	0.65	30.30	89.00	0.79	0.64
6.80	86.97	0.71	0.22	24.75	92.26	0.69	0.65	43.83	83.00	0.78	0.86
10.45	63.66	0.84	0.43	37.05	76.45	0.78	0.86	45.00	66.00	0.71	0.78
14.95	77.53	0.69	0.46	43.35	65.58	0.71	0.78	7.40	41.00	0.98	1.19
19.50	103.80	0.69	0.46								

Tab.8 Predicting values of pile shaft ultimate skin resistance in silt-clay

Void ratio	Liquidity index I_L							
e	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1
0.5	98							
0.6	97	94	91					
0.7		86	84	82	80			
0.8		74	71	69	68	67		
0.9			63	59	56	54	54	
1.0				58	53	49	47	46

The BP model[5] which has a structure of 3-3-1, with study sample given in Tab.7 is applied, that is, there is one input layer with three nodes (e, I_L and depth z), one hidden-layer with three nodes and one output layer with one node. Fig.3 clearly shows that the relationship of the pile resistance is affected by the depth. Within a certain depth, the pile shaft resistance f_s increases with the increase of depth. The critical depth z_0 is just like the conception of critical depth of sandy soil. It is observed that the affect-depth ranges from 20 to 30 m, and the harder the clayey soil consistency (the lower the value of e and I_L) is, the shallower the critical depth is.

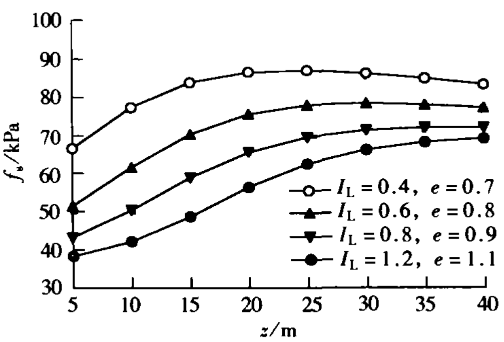

Fig.3 Correlation of pile shaft resistance f_s and silt-clay depth z

4 Conclusions

In this paper PCA is used to discover and identify the meaningful and underlying physical indices of clayey soils in relation to the original data. Furthermore the pile shaft resistance is discussed. The main conclusions can be drawn as follows:

1) PCA is an effective mathematical method in identifying the significance of common physical indices of clayey soils. This method is also helpful to choose minimal or rational index to reflect soil property as wholly as possible.

2) It is not rational that the consistency be classified only by the single index I_L for all the clayey soils. For silt clay, the two indices e and I_L are more practical than the single index I_L. For sandy loam, I_L fails while the void ratio e can reflect its physical state better.

3) It is more rational and accurate that both the void ratio e and the liquidity index I_L be utilized for predicting the pile shaft resistance than single index I_L.

4) For piles in clay soils, the pile shaft resistance affected by depth is clearly observed. The critical depth ranges from 20 to 30 m, and the harder the consistency of the soils, the shallower the critical depth.

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粘土中桩侧摩阻力研究

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摘要: 采用主成分分析方法, 就粘性土多指标反映其性质的规律进行了研究. 研究表明, 采用液性指数作为单一指标的传统粘性土物理状态划分方法, 在反映亚粘土和亚砂土性质时不尽合理. 而采用液性指数 I_L 结合孔隙比 e 反映粉质粘土的特性更加合理. 同样, 孔隙比 e 比液性指数 I_L 能更好地描述亚粘土的天然特性. 采用人工神经网络结合主成分分析, 得出应用孔隙比 e 和液性指数 I_L 两个指标来预测桩侧摩阻力更为精确. 同时发现在一定临界影响深度范围内(20 ~ 30 m), 桩侧摩阻力随深度的增加而增加, 且粘性土的稠度愈硬, 临界深度愈浅.

关键词: 大直径转孔灌注桩; 主成分分析; 人工神经网络; 桩侧摩阻力

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