Statistical Analysis on Physical Properties of Shanghai Soft Clay

Y. M. Lu[1], Y. F. Jin[2], S. L. Shen[3], F. Yu[4] and J. Zhang[5]
[1,2,3]*Department of Civil Engineering and State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai200240, China*
[2,4]*Research Institute in Civil and Mechanical Engineering, Ecole Centrale de Nantes, Nantes 44300, France*
[5]*Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China*
[3]*E-mail:*slshen@sjtu.edu.cn

ABSTRACT: This paper studies the statistical properties of the basic physical parameters of the Shanghai soft clay based on data obtained from extensive literature review and tests conducted by the authors. With the database compiled, the statistics of these parameters are assessed, and regression analyses are conducted to obtain the empirical relationships among them. The goodness-of-fits of normal distribution, log-normal distribution, exponential distribution and uniform distribution are assessed for each parameter using the Kolmogorov-Smirnov (K-S) method. The results show that the normal distribution is suitable for initial water content, specific gravity, plasticity index, liquidity index and unit weight, the log-normal distribution is suitable for initial void ratio and plastic limit, the exponential distribution is suitable only for liquid limit, and the uniform distribution is not recommended.

KEYWORDS: Soft clay, Physical properties, Statistical analysis, Distributional function

1. INTRODUCTION

The process of geological evolution in Shanghai is influenced by many interactional natural factors (Chen, 1957). There were four obvious transgression histories in the city, with different characteristics (Min & Wang, 1979). The influencing area and the thickness of sedimentary strata were relatively large for the transgression in the medium term of late Pleistocene. Global influence can be seen for the transgression in Holocene. The early transgressions in middle and later Pleistocene were weak, resulting in only transitional deposits from marine to continental fancies. In recent years, serious settlement problems have occurred during the engineering constructions in Shanghai, such as building and groundwater pumping (Wu & Sun, 1973). The triaxle tests showed that the engineering properties of Shanghai soft clay were quite unique (Sheng et al., 2013), such as high water content, high water pressure, high compressibility, strong structure and high organic content. This kind of soil is widely spread around the whole city, which is deposited in the middle and late stages of Holocene transgression. Many engineering problems are closely associated to this kind of soil (Huang & Gao, 2005). In this paper, the physical properties of Shanghai soft clay are statistically analysed, which are expected to be helpful to further analyse the variability and reliability of this soil.

The basic physical parameters of soils are widely used in both academic and industrial fields (Sridharan & Nagaraj, 2000; Li et al., 2007; Kariuki, 2003). These parameters may vary under the influences of both natural processes and human disturbances. Thus, how to obtain reasonable parameters and asses their variability is crucial to the design and construction of engineering projects (Shen, 2004). In addition, the distributions of these physical parameters are also important input for risk assessment and reliability analysis. However, very few studies have been conducted to analyse the statistical properties of these parameters. Therefore, the objective of this paper is thus to analyse the statistical properties of the basic physical parameters of the Layer-④ Shanghai soft clay based on extensive literature review supplemented with tests conducted in this paper. Regression analyses are conducted among these parameters. In addition, the suitable distributional functions are obtained for every physical parameters using Kolmogorov-Smirnov (K-S) method.

2. BASIC PHYSICAL PROPERTIES OF SHANGHAI SOFT SOIL

2.1 Sources of information

This paper summarizes the major results of 32 previous publications from 1985 to 2013 regarding the physical properties of Shanghai soft clay. Figure 1 shows the total published papers every year. It can be seen that the tests started to increase in 2004 and reached the maximum in 2011. These tests were conducted mostly by Tongji University, followed by Shanghai Jiao Tong University, and then Shanghai University (Figure 2).

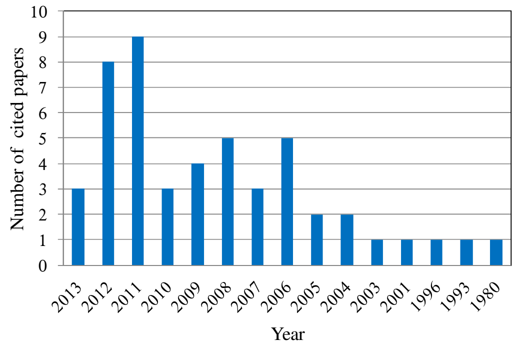

Figure 1 Papers with test data related to Shanghai soft clay (Layer ④) published yearly

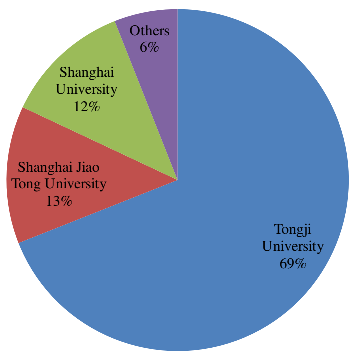

Figure 1 The scientific research units of publishing Shanghai soft clay (Layer④) tests

2.2 Summary of the basic physical properties

All Table 1 summarizes the initial water content, void ratio, specific gravity, liquid and plastic limits and indexes, and unit weight. Large dispersions are usually seen for the obtained data through different in-situ and laboratory tests.

Table 2 summarized the statistics of the basic parameters of the Shanghai soft clay. It can be seen from the table that initial water content under natural states are high, with an average value of 47.97%. The liquid limits are low, with an average value of 20.55%. Some other features can be seen from the coefficient of variation (COV) as follow:

(1) COV less than 0.1 are found for initial water content, initial void ratio and liquid limit, while the values are less than 0.01 for unit weight. This indicates little variations of these parameters for Shanghai soft clay;

(2) The COVs of other parameters are larger than 0.1, indicating that the variability of these parameters should be taken into consideration;

(3) The largest COV occur in plastic and liquid limits. This means special attention should be given to these parameters when using them in engineering practices.

2.3 Empirical relationships

Figure 3 illustrates the relationship between liquid limit (w_L) and plastic index (I_P). All of the obtained data concentrate at the intersection of Lines A and B, with most of them located below Line A and on the right side of Line B. This indicates that this kind of soils range from clay to silt with low liquid limits. Physical properties reflect the engineering characteristics. Thus, summarizing the properties of Shanghai soft clay would be helpful for engineering practices.

Table 1 Basic physical parameters of Shanghai soft clay

Previous papers	Depth (m)	w_0 (%)	e_0	G_s	w_L (%)	w_p (%)	I_P (%)	I_L	γ(KN/m^3)
Sheng *et al.* (2013)	8	-	1.22	-	-	-	18	1.41	16.9
Wu *et al.* (2011)	15.5	41.5	1.15	2.7	44.6	26.5	18.1	0.84	18.6
Sun *et al.* (2010)	12.5	-	-	2.7	44.5	22.4	22.1	0.64	-
Sun & Shen (2010)	9.5	50	1.34	-	41.4	31.2	10.2	1.86	-
Yao *et al.* (2012)	11	47.7	1.4	2.67	-	-	23.5	-	17.8
Yao & Huang (2011)	11	47.7	1.4	2.67	-	-	23.5	-	17.8
Kong *et al.* (2008)	8.25	41.55	1.14	-	51.61	25.7	25.91	0.61	16.95
Ye *et al.* (2006)	-	47.8	1.35	-	44.3	22.8	21.5	1.16	17
Zhang (2007)	11	51.3	1.44	2.75	-	-	21.6	1.28	-
Hong (2008)	-	50.2	1.4	-	43.4	23.2	20.2	1.34	-
Liu (2006)	10.5	46	1.37	2.68	-	-	22.5	-	17
Liu *et al.* (2009)	17	-	1.4	-	-	-	-	-	16.8
Huang & Liu (2011)	10	51.8	1.402	2.74	44.17	22.4	21.77	1.35	-
Tang *et al.* (2008)	11	51.3	1.44	2.75	-	-	21.6	1.28	-
Gao (2013)	-	-	-	2.75	43	19	24	-	-
Tang *et al.* (2012)	-	50.2	1.4	-	43.4	23.2	20.2	1.34	-
Tang *et al.* (2011)	13.5	50.2	-	-	43.4	23.2	20.2	1.34	16.6
Jiang *et al.* (2009)	8.25	41.55	1.14	-	51.61	30.79	20.82	0.52	16.95
Ye *et al.* (2009)	-	49.8	-	-	44.2	24.3	19.9	1.28	17.1
Chen *et al.* (2011)	-	-	1.457	-	-	-	-	-	16.67
Liu & Hou (1996)	-	50.6	1.42	-	-	-	21.2	-	17.1
Chen & Sun (2012)	18	43.8	1.18	-	51.4	27.4	24	-	-
Xu *et al.* (2003)	-	50.7	1.378	2.75	-	-	20.1	-	17.2
Wei (1985)	-	50	1.4	-	42	22	20	1.4	16.95
Wang *et al.* (2011)	12	-	-	-	-	-	-	-	16.7
Wang *et al.* (2007)	-	47	1.35	-	-	-	-	-	-
Zhu *et al.* (2004)	-	47.6	1.32	-	44.1	24	20.1	1.17	17.1
Sheng (2012)	-	44	1.33	-	43.8	24.2	19.6	1.37	16.9
Chen *et al.* (2004)	14.25	52.43	1.73	2.74	44.04	23.27	20.77	1.4	14.1
Gao *et al.* (2004)	9.7	48.5	-	-	-	-	-	-	-
Xiao & Feng (1997)	-	50.6	1.428	-	-	-	-	1.16	17.1
This paper	12	49.6	1.24	-	42.5	22.5	20	1.26	17.2

Note: Only representative data in each paper are listed here, and other data without list are still used for the following analyses.

Table 2 Statistical analyses on Shanghai soft clay

Parameters	Number of measurements	Min.	Max.	Mean	Standard deviation	Coefficient of variation	|R|	Standard deviation	Lower confidence limit	Upper confidence limit
w_0 (%)	30	40	52.43	47.97	3.522	0.07	0.977	0.643	46.71	49.235
e_0	30	1.08	1.73	1.35	0.129	0.096	0.970	0.0235	1.303	1.395
G_s	11	2.67	2.75	2.72	0.034	0.01	0.993	0.010	2.698	2.738
γ(kN/m3)	24	16.6	18.6	17.11	0.429	0.025	0.991	0.087	16.94	17.28
w_L (%)	19	41.4	51.61	44.78	3.12	0.07	0.972	0.7159	43.38	46.18
w_P (%)	19	19	31.2	24.68	3.315	0.134	0.946	0.76	23.19	26.17
I_P (%)	27	10.1	25.91	20.55	3.27	0.159	0.947	0.630	19.32	21.78
I_L	22	0.52	1.86	1.24	0.27	0.22	0.919	0.058	1.127	1.35

Linear functions are the simplest and often used for analysing the physical properties of soils (Que et al., 2007). Linear regression based on the least square method is adopted in this paper. Correlation coefficients among 8 physical parameters are obtained. Regression analyses are conducted for the parameters with correlation coefficients larger than 0.5. The empirical equations are obtained, as shown in Table 3. It can be seen from the table that the correlation coefficient between initial water content and void ratio is the highest. This is because that the soft clay is under the groundwater table. The higher initial void ratio is, the higher initial water content is.

Table 3 Empirical equations for the physical parameters

Number	Species	Empirical functions	Correlation coefficient |R|
1	w_0~e_0	$e_0 = 0.032w_0$-0.16	0.87
2	w_0~ w_L	w_L= -0.46w_0+66.68	0.59
3	w_0~ w_P	w_P= -0.46w_0+47.11	0.62
4	w_0~ I_p	$I_P = 0.064w_0$-1.88	0.81
5	w_0~□	□= -0.10w_0+21.92	0.50
7	e_0~w_L	w_L = -10.56e_0-59.09	0.50
8	e_0~w_P	w_P= -12.35e_0+41.74	0.62
9	e_0~ I_p	I_P= 1.43e_0-0.71	0.66
10	e_0~□	= -4.22e_0+22.69	0.67

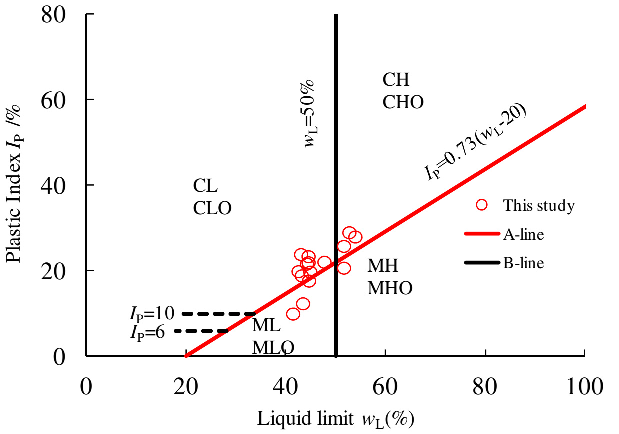

Figure 3 Relationship between liquid limit (w_L) and plastic index (I_P).

3. DISTRIBUTION OF THE PHYSICAL PARAMETERS

3.1 Kolmogorov-Smirnov (K-S) test

Kolmogorov-Smirnov test (K-S test), also named D test, is often used to assess the goodness-of-fit of the observed data to a theoretical model. Suppose that the observational data ($F_n(x)$) fit the theoretical function ($F(x)$), named as H_0 (Function(1)); the opposite hypothesis is named as H_1 (Function(2)).

$$H_0 : F_n(x) = F(x) \tag{1}$$

$$H_1 : F_n(x) \neq F(x) \tag{2}$$

Samples from x_1 to x_n are arranged from small to large, as shown in Function (3).

$$x_{(1)} < x_{(2)} < \cdots < x_{(n)} \tag{3}$$

The accumulative distribution of the samples is described as $F_n(x)$ in Function (4), where $F_n(x)$ is equal to i/n and i is the numbers from 1 to n.

$$F_n(x) = \begin{cases} 0, x < x_{(1)} \\ i/n, x_{(i)} \le x < x_{(i+1)} \\ 1, x < x_{(n)} \end{cases} \tag{4}$$

$F(x)$ is the theoretical function to describe the samples. The largest deviation D_n is obtained by comparing the two distribution functions $F(x)$ and $F_n(x)$ using K-S test.

$$D_n = \max_{-\infty < x < +\infty} \left| F(x) - F_n(x) \right| \tag{5}$$

The two functions are considered to be fit each very well, if the calculated values $F_n(x)$ and $F(x)$ are very close for every samples. In Kolmogorov's theory, there is a parameter to quantitatively analyse the hypothetical distribution function. A critical value is defined as. The function is considered to be acceptable if D_n is less than . K-S test is a widely accepted method because its precision is unlimited to the number of samples. In addition, this method is suitable to the cases with or without sub-groups. That's why this method is chosen in this paper to analysis the physical properties of soils.

3.2 K-S test on Shanghai soft clay

Eight physical parameters are chosen to conduct K-S test, which are the most widely used parameters in the previous papers. They are initial water content, initial void ratio, specific gravity, liquid limit, plastic limit, plastic index, liquid index and unit weight. Taking a = 0.05 as the significance level for the test, the probability distribution is shown in Figure 4.

Table 4 shows the results of K-S test for the eight parameters. It can be seen that the log-normal distribution functions are acceptable for all the parameters except liquid limit. As for the exponential distribution function, it is acceptable for specific gravity, liquid limit, plastic limit, while is unacceptable for others. Uniform distribution function is acceptable for initial water content, specific gravity, plastic limit, and liquid index, while it is unacceptable for others.

The distributional patterns of limited samples may fit well with a couple of distribution functions. However, there is only one best for one parameter. The best function can be obtained either from Figure 4 or through quantitatively comparing the values of D_n (Zhang, 1991). For Shanghai soft clay, normal distribution is the best one for initial water content, specific gravity, plastic index, liquid index and unit weight; logarithmic normal distribution is the best one for initial void ratio, plastic limit; and exponential distribution is the best one only for liquid limit. For some of the parameters, uniform distribution isn't the best choice though it is acceptable.

4. CONCLUSIONS

Based on the review of physical properties of Shanghai soft clay in the previous publications and some additional tests, some statistical work was carried out. The major conclusions may be summarized as follows.

(1) The COVs of initial water content, initial void ratio, specific gravity and liquid limit are less than 0.1, whereas the coefficients of plastic limit, plastic index and liquid index are larger than 0.1. Special attention should be paid to these parameters with large COVs in engineering practices.
(2) The empirical equations for those parameters with correlation coefficients above 0.5 are of great practical importance.
(3) The distributional patterns of initial water content, specific gravity, plasticity index, liquidity index and unit weight can be well described by normal distribution function. Logarithmic normal distribution is suitable only for liquid limit. The results would be a good reference in the analysis of reliability and spatial variability of Shanghai soft soils.

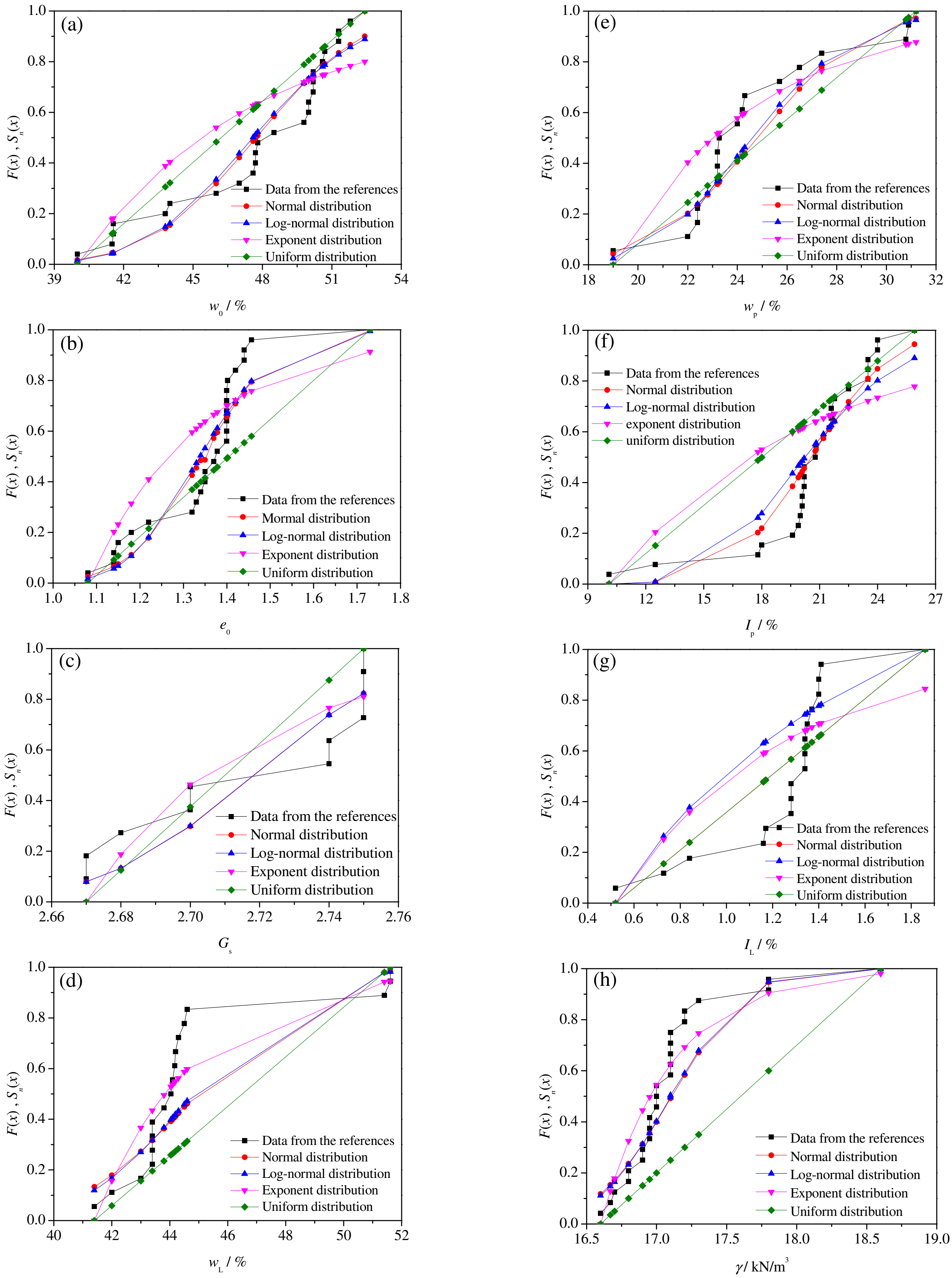

Figure 4 Distribution of K-S goodness of fit test probability

Table 4 K-S goodness of fit test results

Physical Parameters	K-S test							
	Normal distribution		Lognormal distribution		Exponential distribution		Uniform distribution	
	D_n	$D_n^{0.05}$	D_n	$D_n^{0.05}$	D_n	$D_n^{0.05}$	D_n	$D_n^{0.05}$
Initial water content	0.1778	0.264	0.1820	0.264	0.2757	0.264	0.2514	0.264
	$D_n<D_n^{0.05}$ Accept		$D_n<D_n^{0.05}$ Accept		$D_n>D_n^{0.05}$ Reject		$D_n<D_n^{0.05}$ Accept	
Initial void ratio	0.166	0.264	0.1645	0.264	0.3151	0.264	0.38	0.264
	$D_n<D_n^{0.05}$ Accept		$D_n<D_n^{0.05}$ Accept		$D_n>D_n^{0.05}$ Reject		$D_n>D_n^{0.05}$ Reject	
Specific gravity	0.1922	0.391	0.1928	0.391	0.2206	0.391	0.3295	0.391
	$D_n<D_n^{0.05}$ Accept		$D_n<D_n^{0.05}$ Accept		$D_n<D_n^{0.05}$ Accept		$D_n<D_n^{0.05}$ Accept	
Liquid limit	0.3721	0.309	0.361	0.309	0.2349	0.309	0.5199	0.309
	$D_n>D_n^{0.05}$ Reject		$D_n>D_n^{0.05}$ Reject		$D_n<D_n^{0.05}$ Accept		$D_n>D_n^{0.05}$ Reject	
Plastic limit	0.2261	0.309	0.2034	0.309	0.2925	0.309	0.2322	0.309
	$D_n<D_n^{0.05}$ Accept		$D_n<D_n^{0.05}$ Accept		$D_n<D_n^{0.05}$ Accept		$D_n<D_n^{0.05}$ Accept	
Plasticity index	0.1931	0.264	0.2434	0.264	0.4053	0.264	0.4086	0.264
	$D_n<D_n^{0.05}$ Accept		$D_n<D_n^{0.05}$ Accept		$D_n>D_n^{0.05}$ Reject		$D_n>D_n^{0.05}$ Reject	
Liquidity index	0.2285	0.318	0.238	0.318	0.354	0.318	0.277	0.318
	$D_n<D_n^{0.05}$ Accept		$D_n<D_n^{0.05}$ Accept		$D_n>D_n^{0.05}$ Reject		$D_n<D_n^{0.05}$ Accept	
Unit weight	0.2341	0.294	0.2485	0.294	0.4839	0.294	0.4556	0.294
	$D_n<D_n^{0.05}$ Accept		$D_n<D_n^{0.05}$ Accept		$D_n>D_n^{0.05}$ Reject		$D_n>D_n^{0.05}$ Reject	

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