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Study on Engineering Properties of Deep Marine Soft Clay in Guangdong-Hong Kong-Macao Greater Bay Area

Study on Engineering Properties of Deep Marine Soft Clay in Guangdong-Hong Kong-Macao Greater Bay Area

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Abstract. A large number of Marine soft clay are distributed in the Pearl River Delta region of China. The soft clay features mainly on high water content, high sensitivity, high compressibility, low density, low strength and low perviousness, which dramatically restricts local project construction. These features often cause engineering problems such as subgrade settlement, pavement cracking, house cracking, tilting and insufficient bearing capacity of the foundation. Therefore, analyzing the soft clay engineering properties in this area is of great significance for guiding engineering design and construction. Based on the statistic analysis of a large amount of in-situ exploration and experimental data in the western central urban area of Zhuhai, this paper focuses on the distribution and engineering properties of the deep Marine soft clay. The results suggests that the thickness of soft clay is at a range of 10m~ 55.1m. The average water content of soft clay is as high as 68.05%, the plasticity index is 28.16, the fast shear cohesion is only 4.93 kPa, and the internal friction angle is 3.26°. Statistical analysis of layered soft clay shows that the parameters of soft clay vary greatly in depth. The preconsolidation pressure and unconfined compressive strength increases with depth. The water content, liquid limit, plastic limit and plasticity index increase first and then decrease with depth, and the average values reach the maximum values at the depth of 10m ~ 25m. However, the direct shear strength index is on the contrary, and shows a track of decreasing first and then increasing. The minimum values of cohesion and internal friction angle come out at the depth of 10m-25m, with the values of 4.83kPa and 3.10° respectively. The results of in-situ test can better reflect the true mechanical properties of soft clay.

1. Introduction

Soft clay is widely distributed in coastal areas such as Tianjin, Hangzhou, Zhuhai and Wenzhou et al. in China. It has the characteristics of high water content, high sensitivity, low strength and underconsolidation [1~4], which seriously restricts the development and construction of projects in soft clay aera. For these problems, scholars around the world have carried out a large number of studies. Gong Xiaonan et al. analyzed and summarized engineering accidents in soft clay area through typical cases [5]. Kong Lingwei et al. analyzed the Zhanjiang and Haikou soft clay in terms of mineral composition and microstructure [6~7]. Lei Huayang et al. studied the creep characteristics of soft clay through laboratory experiments [8~9]. Yang Xiaojie et al. took the deep soft clay of the fourth runway of Pudong Airport as the research object and analyzed the settlement and deformation law of the deep soft clay under the condition of drainage plate inserted or not inserted [10]. However, due to the influence of sedimentary and environmental factors [11~15], the physical and mechanical parameters of soft clay show strong regional and spatial heterogeneity, the properties of soft clay vary greatly in different regions, and the soft clay in the same region also varies in different depths [16~18].

The Guangdong-Hong Kong-Macao Greater Bay Area (GBA) is located in the Pearl River Delta of China, which comprises the two special administrative regions of Hong Kong and Macao and the cities of Guangzhou, Shenzhen and Zhuhai, is the most open and economically dynamic region in China. A large number of deep Marine soft clay is widely distributed in this area. Since the properties of soft clay are not fully understood, many engineering diseases are caused during the exploitation and construction in this area [19], as shown in Figure 1. Therefore, before the development and construction, it is necessary to conduct detailed investigation and research on the properties of soft clay in this region, so as to provide guidance and accumulate experience for the engineering construction in the Guangdong-Hong Kong-Macao Greater Bay Area and other similar areas with deep Marine soft clay.

(a) Severe ground sinking outside the house. (b) Uneven settlement of Zhuhai express.

Figure 1. Uneven settlement of Marine soft clay area.

2. Description of the project

2.1 Project overview

Taking the western central urban area of Zhuhai, the core area of the Guangdong-Hong Kong-Macao Greater Bay Area, as an example. Zhuhai plans to invest ¥ 100 billion in infrastructure in five years to build a sub-urban center in the west of Zhuhai. The geological conditions in this area are poor and the deep soft clay covers a large area. Part A of the western central urban area of Zhuhai is a major start-up project, covering an area of about 11.35 km^2 (Figure 2-3).

2.2 Engineering geological condition

The western central urban area of Zhuhai is mainly composed of low mountains, hills, estuarine plains and tidal flats. The exposed strata in the site mainly include artificial filling soil layer (Q_4^{ml}), Quaternary

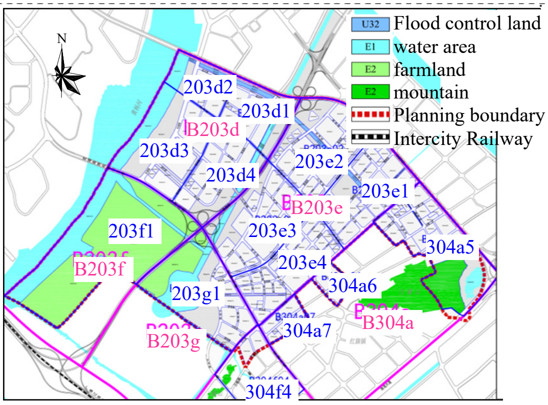

Figure 2. Control planning of central urban of western Zhuhai.

Figure3. Scene of central urban of western Zhuhai.

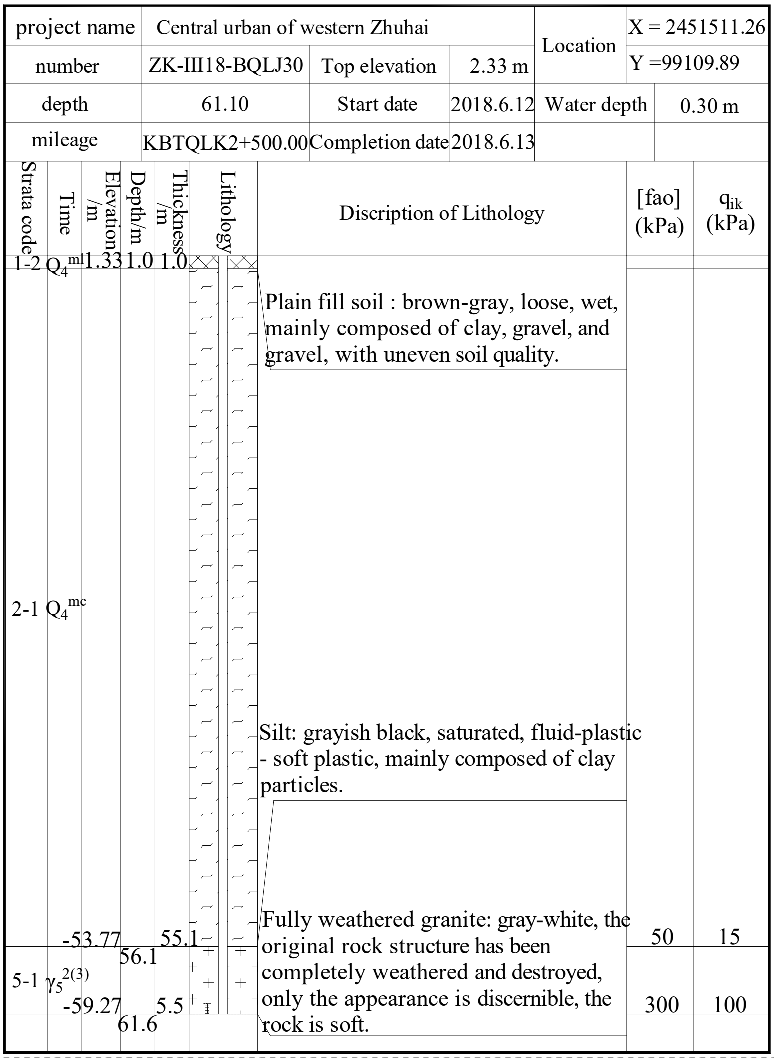

Figure 4. Typical Geological histogram.

marine and continental sedimentary layer (Q_4^{mc}) and Quaternary eluvial layer (Q_4^{el}). The underlying bedrock is granite (γ_5^{2-3}). Quaternary Marine and continental sedimentary layers (Q_4^{mc}) are widely distributed in the western central urban area of Zhuhai, and area reaches about 200km^2.At present, the exposed maximum depth of the soft clay is 56.1 m, with an average thickness of 30.37 m. Typical geological sections are shown in Figure 4.

3. Physical and mechanical properties and distribution of soft clay

Table 1. Statistical table of physical and mechanical parameters.

Parameters	Sample size (N)	Distribution	Mean value (u)	Standard deviation (σ)	Variable coefficient ($C.V$)
Water content/w (%)	890	40.80 ~98.60	68.05	9.08	0.133
Density/ ρ (g/cm^3)	890	1.42~1.86	1.59	0.07	0.041
Dry density/ ρ_d (g/cm^3)	890	0.74~1.33	0.95	0.09	0.092
Specific gravity/Gs	890	2.62 ~2.67	2.63	0.01	0.003
Ratio/e	890	1.00 ~2.56	1.79	0.25	0.138
Porosity/n (%)	890	49.98~71.94	63.89	3.21	0.050
Saturation/Sr (%)	890	79.33 ~100.0	98.73	2.07	0.021
Liquid limit/w_L (%)	890	36.70 ~87.30	63.02	7.77	0.123
Plastic limit/ w_P (%)	890	18.60 ~50.80	34.86	4.86	0.139
Plasticity index/I_P	890	14.60 ~43.50	28.16	4.69	0.166
Liquidity index/I_L	890	1.02 ~1.90	1.18	0.14	0.121
Coefficient of compressibility/a_v (MPa^{-1})	890	0.53 ~3.74	1.55	0.52	0.336
Modulus of compressibility/Es(MPa)	890	0.77~3.52	1.71	0.49	0.287
Vertical coefficient of consolidation/C_v (10^{-3}cm^2/s)	209	0.17 ~3.71	0.86	0.68	0.710
Horizontal coefficient of consolidation C_H (10^{-3}cm^2/s)	17	0.61 ~1.66	0.88	0.29	0.249
Preconsolidation pressure/Pc (kPa)	165	17.70~91.70	52.03	18.63	0.358
Cohesion/c (kPa)	149	3.00~11.42	4.93	1.04	0.210
Internal friction angle/ φ (°)	149	2.01 ~7.52	3.26	0.61	0.186
Unconfined compressive strength/qu(kPa)	145	4.20 ~96.36	23.23	14.48	0.623
Sensitivity/St	139	1.10 ~4.40	2.40	0.57	0.239
Vertical permeability coefficient/k_v(cm/s)	139	1.12E-07~1.93E-05	1.87E-06	2.93E-06	1.564
Horizontal permeability coefficient/k_h (cm/s)	7	4.14E-08~9.73E-06	3.53E-06	7.73E-06	2.187
Organic content /O_m (%)	124	2.11 ~5.90	3.58	1.11	0.309

Through a large number of drilling investigations, laboratory and in situ tests, the characteristics of soft clay were statistically analyzed. The statistical parameter are shown in Table 1. Song Xugen et al. drew a distribution contour map of soft clay based on the survey results [13], as shown in Figure 5. The thickness of soft clay is not uniformly distributed, with the thickness between 10 and 55.1m.

As can be seen from Table 1. The marine sedimentary soft clay has high water content, high ratio, high compressibility and low shear strength. The mean value of internal friction angle of the quick shear test was 3.26° and the mean value of cohesion was 4.93kPa.

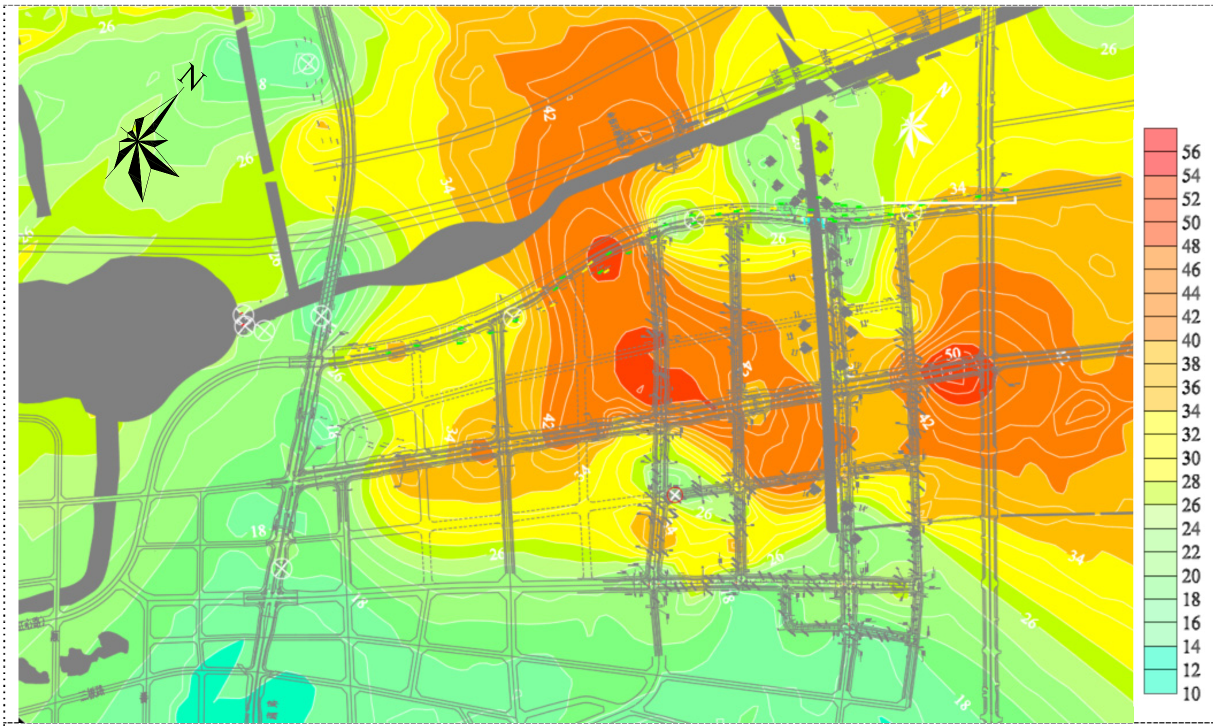

Figure 5. Contour map of Part A in central urban of western Zhuhai.

4. The law of physical parameters changed with depth

According to the investigational results, the curves of physical parameters and mechanical parameters of soft clay changed with depth of typical boreholes are drawn in Figure 6 and Figure 11. The physical and mechanical indexes of soft clay with different depths of 0m~5m, 5m~10m, 5m~10m, 10m~15m, 15m~20m, 20m~25m, 25m~30m, 30m~35m, 35m~40m and 40m~45m were statistically analyzed, as shown in Table 2. Figures 7-10 show the mean physical parameters of soft clay changed with depth. Figure 12 show the curve of the mean mechanical parameters of soft clay changed with depth. According to the cone penetration test results, the hammer resistance and lateral friction resistance curves of a typical test hole (JC-Ⅲ 18-BQ18) changed with depth are obtained, as shown in Figure 13.

4.1 physical parameters of soft clay of single borehole Changed with depth

As can be seen from Figure 6, the water content, liquid limit and plastic limit of soft clay in ZK-Ⅲ14-XF2#03 increased first and then decreased. The maximum water content reaches 93.40% at 14.5m, 85.70% at 18.5m, and decreases to 76.20% at 22.5m. The average water content is 85.10% at 10.5m - 22.5m, which is 1.28 times of other depths. The liquid limit is 73.00% at 14.5m, 73.80% at 18.5m, 73.60% at 22.5m. At 10.5m - 22.5m, the liquid limit is 73.50%, which is 1.18 times of other depths. The plastic limit is 46.30% at 14.5m, 43.50% at 18.5m and 41.40% at 22.5m. The average plastic limit is 43.70% at 10.5m - 22.5m, which is 1.24 times of other depths. The coefficient of compressibility, liquidity index and ratio also increased first and then decreased with depth, and reached the maximum value in the middle of the soft clay layer at a depth of 14.5m. The plasticity index does not change with the depth basically and the curve approximates a horizontal line. The variation law of Modulus of compressibility with depth is opposite to that of water content, and it reaches the minimum value of 0.92MPa at the depth of 14.5m.

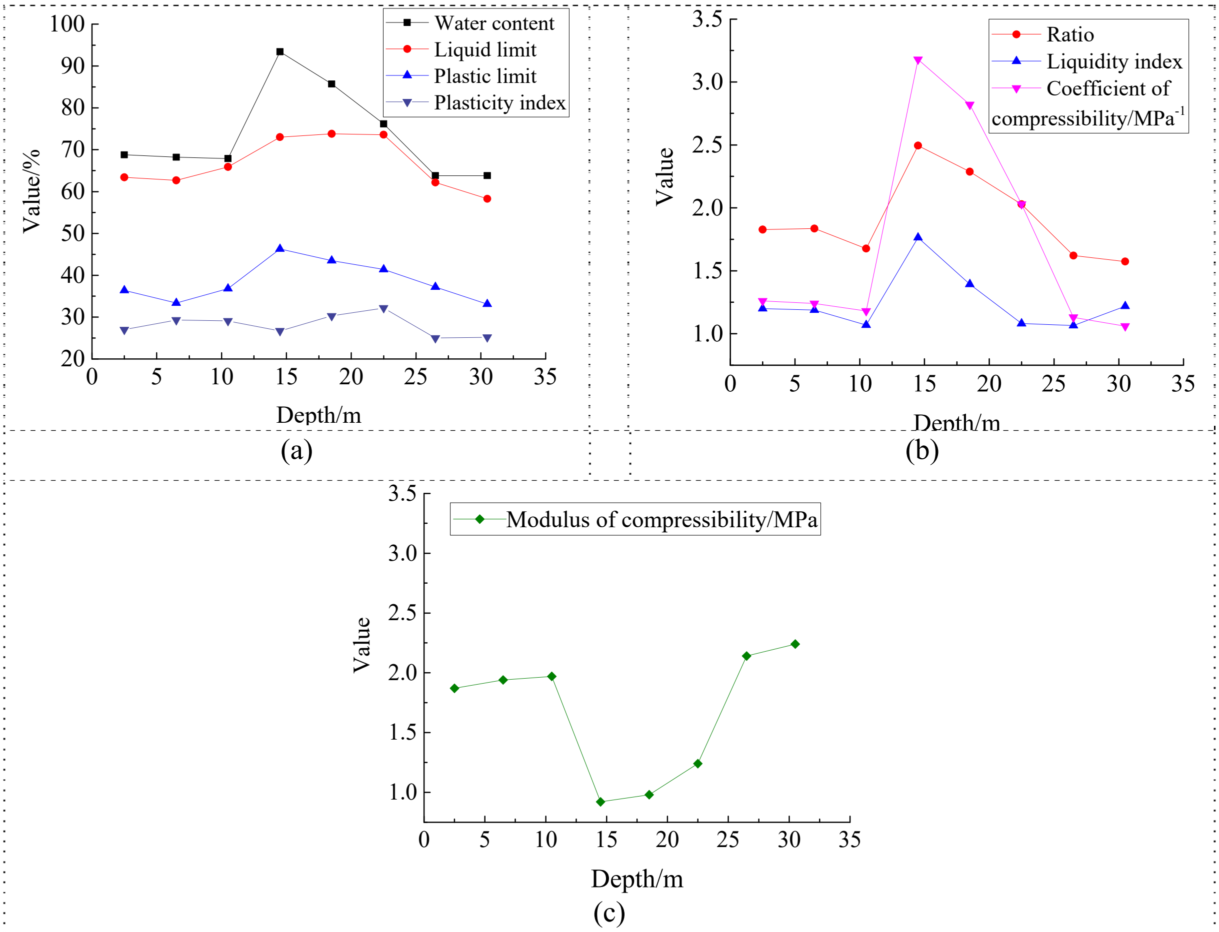

Figure 6. Curves of physical parameter of drilling hole ZK-III14-XF2#03 changed with depth

4.2 mean values of physical parameters of soft clay Changed with depth

Because the results obtained from a single borehole are affected by humans factor. In order to obtain more reliable statistical results, more than 1100 samples were classified according to the sampling depth, and the changes of their physical parameters with the depth were statistically analyzed.

As can be seen from Figure 7(a), Figure 7(b) and Table 2, the statistical law of water content, liquid limit, plastic limit and plasticity index of soft clay in the western central urban of Zhuhai increases firstly and then decreases with depth. The mean value of water content is 72.32% at 10m~15m, 73.96% at 15m~20m, and 71.26% at 20 m ~ 25m.The mean value of liquid limit is 71.51% at 10m~25m, which is 1.12 times of other depths. The liquid limit is 66.36% at 10m~15m, 67.90% at 15m~20m, and 67.10% at 20~25m.The mean value of liquid limit is 71.51% at 10m~25m, which is 1.13 times of the other depths. The mean value of plastic limit is 36.63% at 10m~15m, 37.56% at 15m~20m, and 36.77% at 20~25m.The liquid limit is 36.99% at 10m~25m, which is 1.13 times of the average liquid limit at other depths. The mean value of plasticity index is 30.40% at 10m~15m, 30.34% at 15m~20m, and 29.59% at 20~25m.The mean value of liquid limit at 10m~25m is 30.11%, which is 1.12 times of other depths. As can be seen from Figure 7(c), Figure 7(d) and Table 2, the curves of ratio and coefficient of compressibility changed with time also increases at first and then decreases. The mean values of ratio and coefficient of compressibility at 15m~20m in the middle of soft clay reach the maximum of 1.95

and 1.92, respectively. But the mean value of liquid index changes little with depth and the curve is basically a horizontal line. The curve of modulus of compressibility decreases first and then increases with the change of depth, and reaches the minimum value of 1.39MPa at 15m~20m.

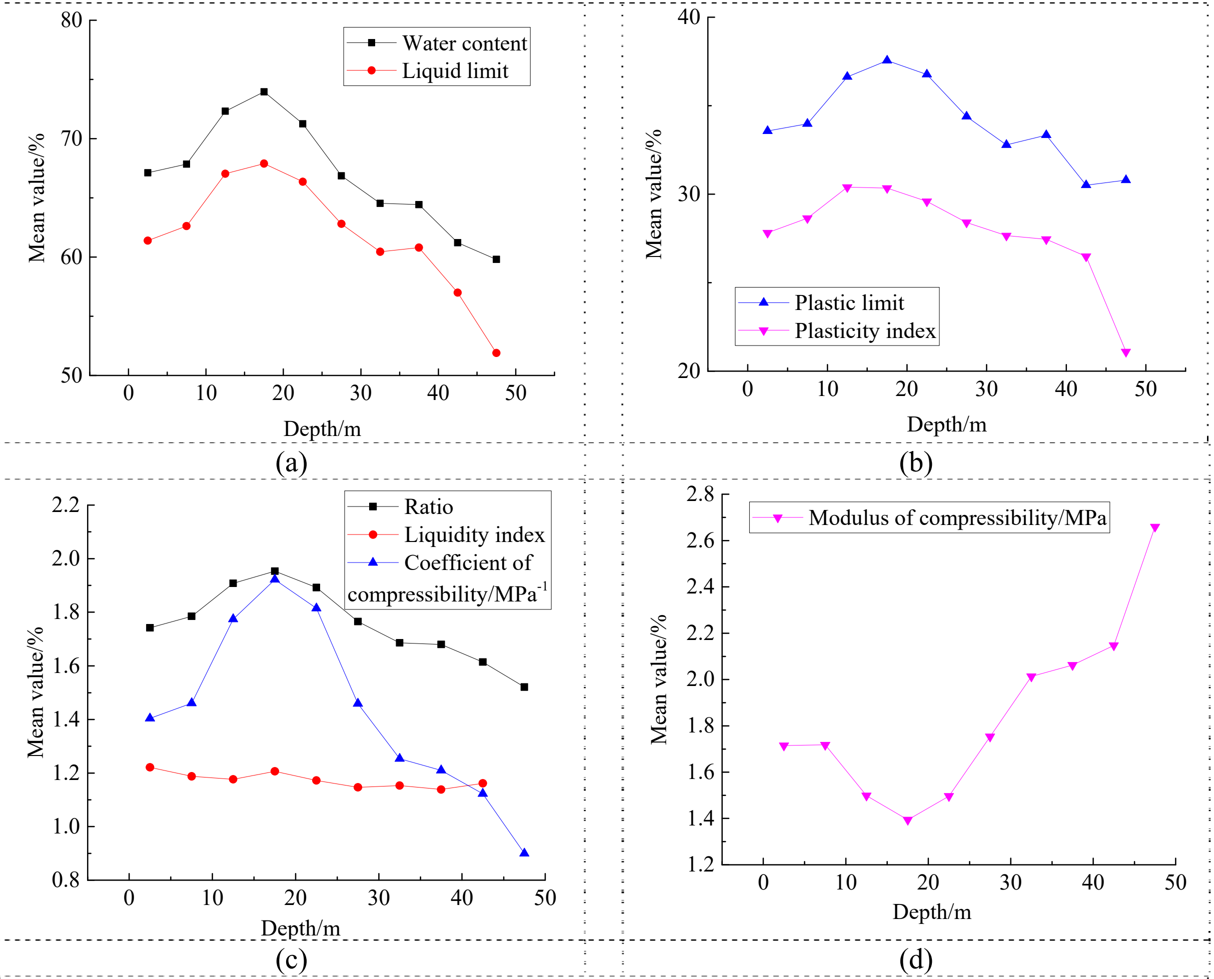

Figure 7. Curves of mean value of physical parameter changed with dept

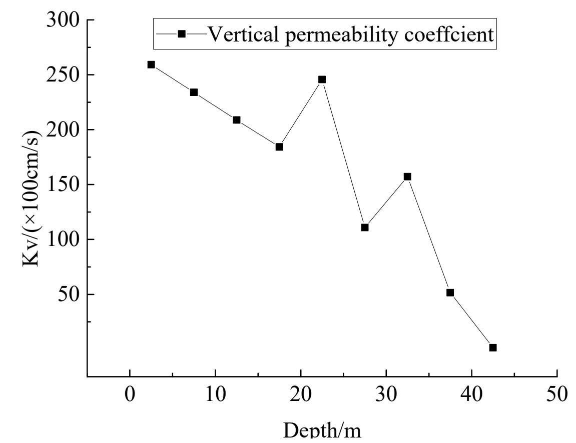

Figure 8 Curves of mean value of Permeability coefficient changed with depth.

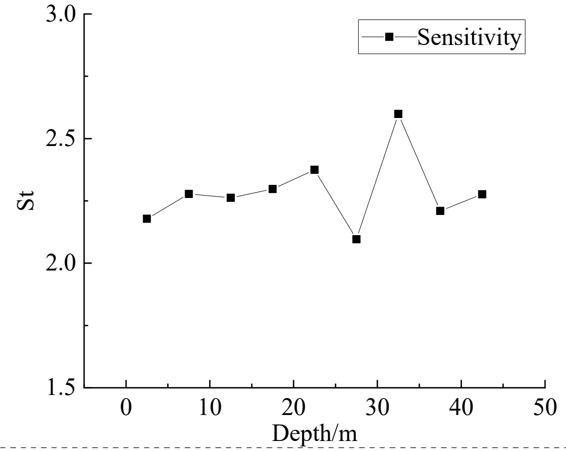

Figure 9 Curves of mean value of sensitivity changed with depth.

Table 2. Physical and mechanical parameters average value changed with depth.

depth（m）	parameter	w(%)	e	w_L	w_p	I_P	I_P	a_v	Es	Pc	c	φ	q_u	S_t	O_m	k_v
0~5	N	142	142	142	142	142	142	142	142	39	63	63	44	42	30	32
	u	67.12	1.74	61.39	33.57	27.82	1.22	1.40	1.71	38.38	5.05	3.25	12.65	2.18	3.10	2.59E-05
	σ	4.82	0.13	5.20	3.46	4.27	0.17	0.28	0.33	23.08	1.19	0.57	5.43	0.74	0.56	3.04E-05
	C.V	0.07	0.07	0.08	0.10	0.15	0.14	0.20	0.19	0.60	0.23	0.17	0.43	0.34	0.18	1.17
5~10	N	156	156	156	156	156	156	156	156	30	71	71	16	15	19	36
	u	67.85	1.78	62.62	33.98	28.64	1.19	1.46	1.72	39.94	5.00	3.18	17.37	2.28	3.09	2.34E-05
	σ	6.30	0.18	5.17	3.42	4.26	0.14	0.39	0.42	21.12	0.84	0.49	5.89	0.53	0.66	3.15E-05
	C.V	0.09	0.10	0.08	0.10	0.15	0.12	0.27	0.24	0.53	0.17	0.15	0.34	0.23	0.21	1.34
10~15	N	160	160	160	160	160	160	160	160	24	78	78	24	23	10	32
	u	72.32	1.91	67.04	36.63	30.40	1.18	1.77	1.50	39.94	4.91	3.10	18.35	2.26	3.70	2.09E-05
	σ	9.56	0.26	7.70	5.23	5.17	0.15	0.56	0.35	22.34	0.92	0.45	6.47	0.60	1.03	2.63E-05
	C.V	0.13	0.14	0.11	0.14	0.17	0.12	0.32	0.24	0.56	0.19	0.14	0.35	0.27	0.28	1.26
15~20	N	146	146	1461	146	146	146	146	146	30	67	67	30	29	25	31
	u	73.96	1.95	67.90	37.56	30.34	1.21	1.92	1.39	44.12	4.83	3.11	20.48	2.30	3.67	1.84E-05
	σ	8.10	0.23	6.90	5.02	4.14	0.17	0.52	0.31	18.65	0.90	0.43	7.13	0.60	0.85	2.86E-05
	C.V	0.11	0.12	0.10	0.13	0.14	0.14	0.27	0.23	0.42	0.19	0.14	0.35	0.26	0.23	1.55
20~25	N	120	120	120	120	120	120	120	120	19	58	58	10	10	8	25
	u	71.26	1.89	66.36	36.77	29.59	1.17	1.81	1.50	51.19	4.87	3.12	27.01	2.37	4.74	2.46E-05
	σ	8.86	0.23	7.63	4.75	4.59	0.16	0.58	0.37	17.75	0.99	0.41	10.44	0.85	2.33	2.94E-05
	CV	0.12	0.12	0.11	0.13	0.16	0.13	0.32	0.25	0.35	0.20	0.13	0.39	0.36	0.49	1.20
25~30	N	76	76	76	76	76	76	76	76	10	36	36	12	11	12	9
	u	66.86	1.77	62.80	34.39	28.41	1.15	1.46	1.75	68.23	5.00	3.26	41.78	2.10	4.46	1.11E-05
	σ	4.54	0.13	4.45	3.28	3.66	0.06	0.34	0.35	16.58	0.90	0.51	23.94	0.48	1.54	3.00E-05
	C.V	0.07	0.08	0.07	0.10	0.13	0.05	0.23	0.20	0.24	0.18	0.16	0.57	0.23	0.34	2.71
30~35	N	48	48	48	48	48	48	48	48	13	23	23	7	7	7	8
	u	64.54	1.69	60.44	32.79	27.65	1.15	1.25	2.01	68.18	5.36	3.30	33.88	2.60	4.21	1.57E-05
	σ	2.87	0.10	3.63	3.02	3.92	0.07	0.26	0.41	14.25	0.81	0.62	11.62	0.33	0.69	2.00E-05
	C.V	0.04	0.06	0.06	0.09	0.14	0.06	0.21	0.20	0.21	0.15	0.19	0.34	0.13	0.16	1.27
35~40	N	32	32	32	32	32	32	32	32	5	15	15	5	5	4	3
	u	64.44	1.68	60.80	33.34	27.46	1.14	1.21	2.06	74.08	5.53	3.35	36.37	2.21	3.42	5.15E-06
	σ	4.01	0.10	4.39	2.30	3.81	0.08	0.22	0.41	16.81	1.15	0.49	13.73	0.65	0.98	8.10E-06
	C.V	0.06	0.06	0.07	0.07	0.14	0.07	0.18	0.20	0.23	0.21	0.15	0.38	0.29	0.29	1.57
40~45	N	14	14	14	14	14	14	14	14	1	5	5	2	2	1	2
	u	61.21	1.61	57.00	30.51	26.49	1.16	1.12	2.15	67.70	5.49	3.61	36.91	2.28	4.20	1.46E-07
	σ	4.07	0.07	5.11	3.55	2.36	0.08	0.16	0.32	/	1.23	0.47	3.22	0.02	/	1.37E-07
	C.V	0.07	0.04	0.09	0.12	0.09	0.07	0.14	0.15	/	0.22	0.13	0.09	0.01	/	0.94

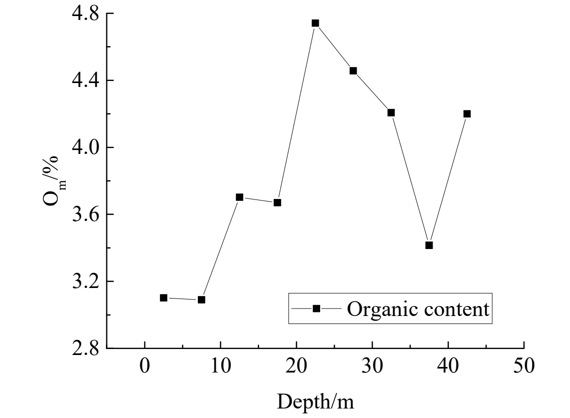

Figure 10. Curves of mean value organic content changed with depth.

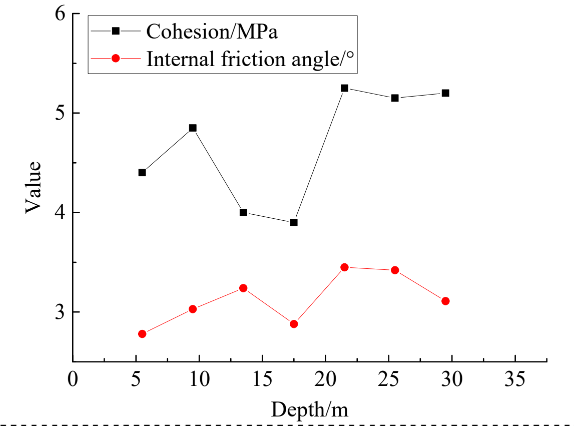

Figure 11 Curves of mechanical parameters of ZK-III14-XF2#03 changed with depth.

It can be seen from Figure 8 that the curves of permeability coefficient decrease with the increase of depth, and the permeability coefficient varies greatly with the depth. The permeability coefficient is 2.59E-05 at 0m-5m and becomes 1.46E-07 at 40-45m, which is consistent with the research results of loess tableland and riverbed sediments [20]. As can be seen from Figure 9 and Figure 10, the sensitivity and organic matter content of soft clay are basically unrelated to depth. For example, the sensitivity is 2.18 at 0m - 5m, 2.28 at 5m - 10m, 2.26 at 10m - 15m, 2.30 at 15m - 20m, 2.37 at 20m - 25m, 2.10 at 25m-30m, 2.60 at 30m-35m, 2.21 at 35m-40m, and 2.28 at 40m~44m.

5. The law of mechanical parameters changed with depth

It can be seen from Figure 11 that the cohesion of ZK-Ⅲ14-XF1#06 varies with depth and reaches the minimum value of 3.9 kPa in the middle of the soft clay at 17.5m (Figure 12), but the internal friction angle changed with depth is not obvious.

In order to eliminate the influence of human factors on a single borehole, the mean value of mechanical parameters of more than 1100 samples were statistically analyzed. The results are shown in Table 2 and Figure 13. As can be seen from Figure 13(a), the curve of mean value of cohesion changed with depth decreasing first and then increasing, and the mean value is 4.91kPa at 10m~15m, 4.83kPa at 15m~20m, and 4.87kPa at 20~25m.The mean value of cohesion is 4.87kPa at 10m~25m, which is significantly lower than that in other regions. The variation law of average internal friction angle with depth is similar to that of cohesion. The mean value of internal friction angle is 3.10° at 10m~15m, 3.11° at 15m~20m, 3.12° at 20~25m, 3.11° at 10m~25m. The cohesiveness at 10m - 25m is small than the mean value of other depths. It can be seen from Figure 13(b) that the unconfined compressive strength and the preconsolidation pressure increase with the depth. The unconfined compressive strength is 12.6kPa at 0m - 5m and 36.37kPa at 40m - 45m.The mean value of the initial consolidation pressure is 38.37kPa at 0m - 5m, and 67.70kPa at 40m -45m.

According to the results of cone penetration test (Figure 13), the variation law of hammer resistance q_c and friction resistance f_s of Jc-Ⅲ18-BQ18 with depth decreases first and then increases, reaching the minimum at the depth of 3m~5m. At the position of 3m~5m, q_c is 170kPa, f_s is 4.0kPa. And then increases as the depth add. The in-situ test results comprehensively reflect the influence of water content, depth changes, etc., and can better reflect the true mechanical properties of the soil.

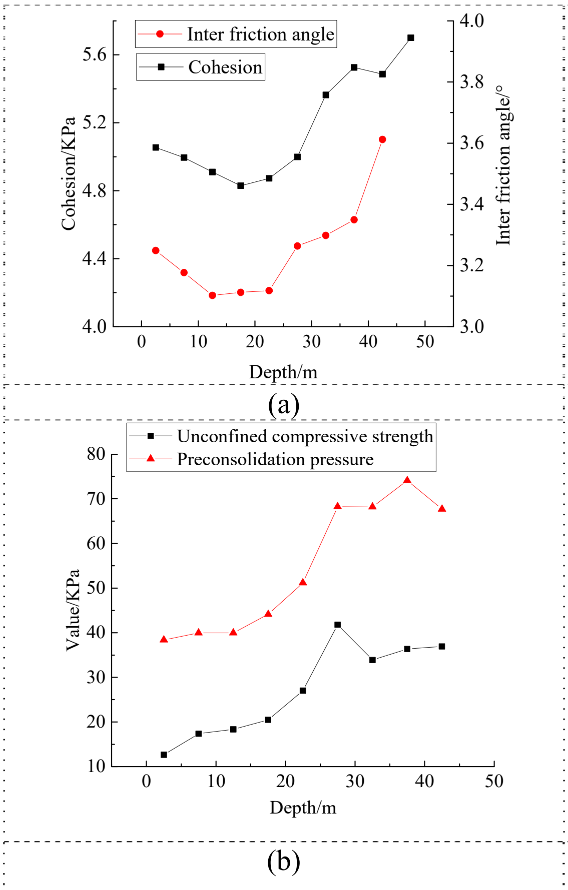

Figure 12 Curves of mean value of mechanical parameters changed with depth.

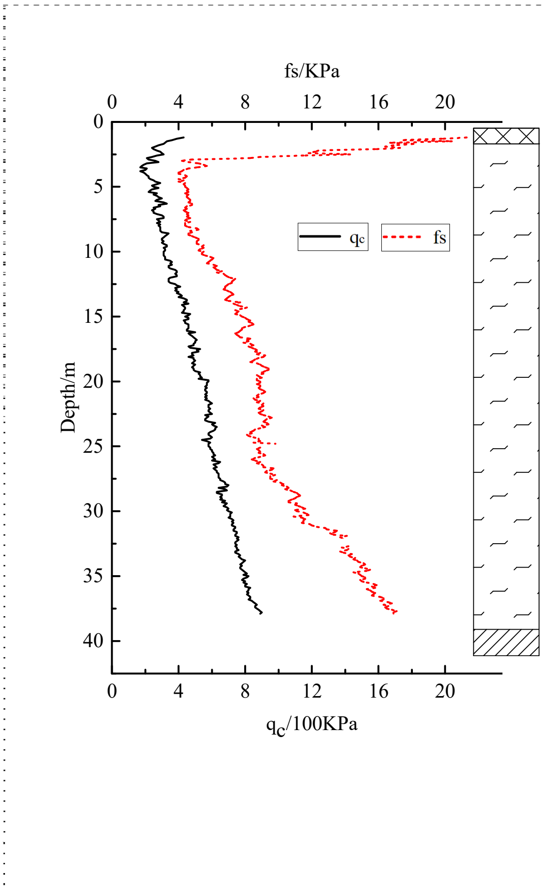

Figure 13. Curves of results of cone penetration test.

6. Conclusions

Based on a large number of data analysis of the soft clay in the western central urban of Zhuhai, this paper comprehensively and systematically analyzed the law of the physical and mechanical parameters of the soft clay in the western central urban of Zhuhai changed with the space. The research results are of great significance for guiding the soft foundation treatment and engineering construction in the western central urban of Zhuhai. The conclusions are as follows.

(1) The thickness of soft clay is not uniformly distributed, with the thickness between 10 and 55.1m. It can be seen from the physical and mechanical parameters of soft clay that the water content of soft clay is up to 68.05%, the coefficient of compressibility is up to 1.55, and the plasticity index is up to 28.16. The shear strength is low, the fast shear cohesion is only 4.93kPa, and the internal friction Angle is 3.26°.

(2) The physical and mechanical properties of soft clay are quite different in the same plane at different depths. And this properties should be considered when designing and calculating.

(3) Parameters such as unconfined compressive strength and preconsolidation pressure are affected by depth and increase with depth. The mean value of unconfined compressive strength is 12.6 kPa at 0m - 5m and increased to 36.37 kPa at 40m - 45m. The mean value of the initial consolidation pressure is 38.37kPa at 0m - 5m and increased to 67.70kPa at 40m - 45m. But the permeability coefficient is on the country, with an average value of 2.59E-05 at 0m - 5m and decreased to 1.46E-07 at 40 - 45m. The sensitivity and organic matter content are not affected by the depth change.

(4) The water content increases first and then decreases with the change of depth. The mean values of water content, liquid limit, plastic limit and plasticity index at the depth of 0m~5m are 67.12%, 61.39%, 33.57% and 27.83%, respectively. At depths of 10m-25m, the mean values reach the maximum of 73.96%, 66.36%, 37.56% and 30.34%. Then the mean values of water content, liquid limit, plastic limit and plasticity index at the depth of 40m~45m decreased to 61.21%, 57.00%, 30.51% and 26.49%, respectively.

(5) The variation law of cohesion and internal friction angle with depth is opposite to that of water content. The mean values of fast shear cohesion and internal friction angle at depth 0m~5m are 5.05kPa and 3.25°, respectively. At the depth of 10m~25m, the mean value decreased to 4.83kPa and 3.10°. And then, the mean value of cohesion and internal friction angle increases to 5.49kPa and 3.61° at the depth of 40m- 45m. In the design of excavation support and foundation treatment, attention should be paid to the stability of the depth of 10m~25m.

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