

Consolidation settlement of soil foundations containing organic matters subjected to embankment load

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Abstract. Peatland is distributed in China widely, and organic matters in soil frequently induce problems in the construction and maintenance of highway engineering due to the high permeability and compressibility. In this paper, a selected site of Dali-Lijiang expressway was surveyed in China. A numerical model was built to predict the settlement of the foundation of the selected section employing the soft soil creep (SSC) model in PLAXIS 8.2. The model was subsequently verified by the result of field observance. Consequently, the parameters of 17 types of soils from different regions in China with organic contents varying from 1.1-74.9% were assigned to the numerical model to study the settlement characteristics. The calculated results showed that the duration of primary consolidation and proportion of primary settlement in the total settlement decreased with increasing organic content. Two empirical equations, for total consolidation settlement and secondary settlement, were proposed using multiple linear regression based on the calculated results from the numerical models. The analysis results of the significances of certain soil parameters demonstrated that the natural compression index, secondary compression index, cohesion and friction angle have significant linear relevance with both the total settlement and secondary settlement, while the initial coefficient of permeability exerts significant influence on the secondary settlement only.

Keywords: foundation; soft soil creep model; secondary settlement; organic content; expressway embankment

1. Introduction

Organic matters in soils are undecomposed plant remains. Soils containing organic matters are distributed widely in China. Figure 1 shows the distribution of organic carbon in China (Ma 2013), where the reserves of organic carbon reflect the reserves of organic matters. Due to an increasing need in transportation among regions, it is inevitable for highways to cross regions with organic-matter-laden soil. However, the settlement of organic-matter-laden site may be long-term, large, and sometimes differential, as reported by observations of Pronger *et al.* (2014) at New Zealand and Samson (1985) at the Montreal. Many scholars have made efforts to study and find effective ways to enhance the engineering properties of peat soil foundations. Jorat *et al.* (2013) reported the utilization of sand columns to accelerate the consolidation process of peat and studied the influence of sand additive on the mechanical behavior of peat. Kalantari *et al.* (2010, 2011, 2015) proposed the stabilization of peat soil with various additives, such cement, polypropylene, and steel fibres. However, countermeasures should vary with consolidation stages of peat soil to control the post-construction settlement. For the control of post-construction primary compression, measures which accelerate the drainage of

pore water are preferred, such as sand columns (Jorat *et al.* 2013). While for the control of post-construction secondary compression, measures which stabilize the soil and eliminate the secondary compression potential are preferred, such as cement stabilization (Dehghanbanadaki *et al.* 2020), geosynthetic reinforcement (Gouw 2020, Puppala *et al.* 2020), and surcharge loading (Gouw 2020). It is essential for scholars and engineers to reasonably assess the primary and secondary settlement of the organic-matter-laden soil to suggest feasible countermeasures.

The organic matters are so porous, bendable, and compressible that they significantly change the properties of soil, especially compression and permeability (Boulanger *et al.* 1998, Sridharan and Nagaraj 2001, Mesri 2002, Laloui and Ferrari 2013, Mesri 2013, Huat *et al.* 2014, Madaschi and Gajo 2015, Rezanezhad *et al.* 2016). For instance, the secondary compression index of peat changes with time, unlike soft soils (Mesri and Ajlouni 2007). Many researchers have investigated the physical properties of natural peat soils in different regions of China such as Jilin (Liu 2006, Xu 2008, Liu *et al.* 2010, Mao 2015), Yunnan (Xiong 2005, Yu 2015), Hangzhou (Wang 2013, Zhao 2014, Yang *et al.* 2016), and Xinjiang (Zhang 2016), and the physical properties of soil samples show a great spatial variance. However, it is noted that organic content has significant correlations with other physical indexes as one of the most important physical indexes for soil containing organic matters, and it could be used to predict the consolidation behavior of soil (Sun 2006, Lv *et al.* 2011, Mao 2015, Wang *et al.* 2017). For the sake of the influence degree assessment of organic matters on mechanical properties of soil, soils containing organic matters are

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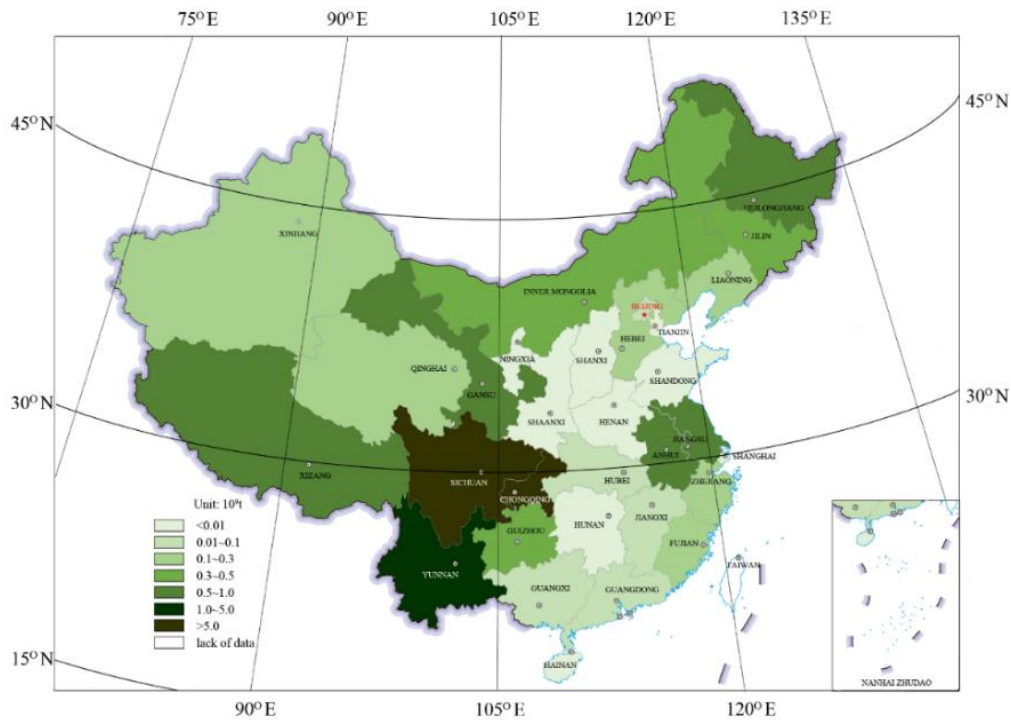


Fig. 1 Organic carbon reserves in China (Ma 2013)

categorized as organic soil (organic content, w_u : $5\% \leq w_u < 10\%$), weak peaty soil ($10\% \leq w_u < 25\%$), medium peaty soil ($25\% \leq w_u < 40\%$), strong peaty soil ($40\% \leq w_u < 60\%$), and peat ($w_u \geq 60\%$), according to *Code for investigation of geotechnical engineering* of China (GB 50021-2001, Ministry of Construction of People's Republic of China).

The consolidation process of soil is divided into the primary and secondary consolidation, where the primary consolidation represents the process of pore pressure dissipation and the secondary consolidation represents the process of the rearrangement and compression of soil grains after the primary consolidation. By far, many methods have been developed to predict secondary compression, such as multi-layer analysis (Mesri and Choi 1985), the uniaxial constitutive model based on Perzyna's extended overstress theory (Madaschi and Gajo 2017), the elasto-viscoplastic modeling method (Karunawardena *et al.* 2011), and the extended macro element method (Nguyen *et al.* 2015, Tashiro *et al.* 2015, Yamada *et al.* 2015). The soft soil creep (SSC) model (al-Khoury 2002) is a simple but effective method to predict the behavior of peat soils and has been applied in many studies (e.g., Tan 2008, Mujah *et al.* 2016, Tyurin and Nevzorov 2017, Buttling *et al.* 2018, Gong and Chok 2018, Wong and Somanathan 2019).

It is important to assess the primary and secondary settlement of organic-matter-laden site, as the countermeasures may vary with different consolidation stages. Besides, many previous studies (e.g. Tashiro *et al.* 2015, Acharya *et al.* 2017, Wong and Somanathan 2019) only focus on one or two types of soils containing organic matters, and thus are not representative enough to express the general influence of organic matters on the compression characteristics. In this study, the SSC model is used to simulate the compression characteristics of an expressway

foundation, and the calculated settlement results are compared with the field observations to validate the SSC model. Subsequently, numerical models, which employ the SSC model and the parameters of 17 types of organic-matter-laden soils varying in organic content, are built to study the influence of organic content on the compression characteristics of foundations. Two empirical models are established to predict the total settlement and secondary settlement according to the calculated results of numerical simulation, and the significances of soil physical parameters are discussed. This paper would be helpful for scholars and engineers to assess the primary and secondary settlement of organic-matter-laden foundation subjected to embankment load and to select proper countermeasures.

2. Verification of the SSC model

2.1 Site description

The Dali-Lijiang Expressway (G5611) is a link road of the Hangzhou-Ruili Expressway (G56), which is an important trunk line of China's expressway network. It is located in Yunnan Province and passes through many peatlands. Fig. 2 shows the alignment of the Dali-Lijiang Expressway and the distribution of organic carbon density in Yunnan. The density of organic carbon partially reflects the organic content of soil. It is notable that the Dali-Lijiang Expressway passes a region of Yunnan that is high in organic carbon density. A road section (K87 + 535) located on peatland in Eryuan County was considered to be representative and was thus selected as the test site.

The profile of the studied section is shown in Fig. 3. The

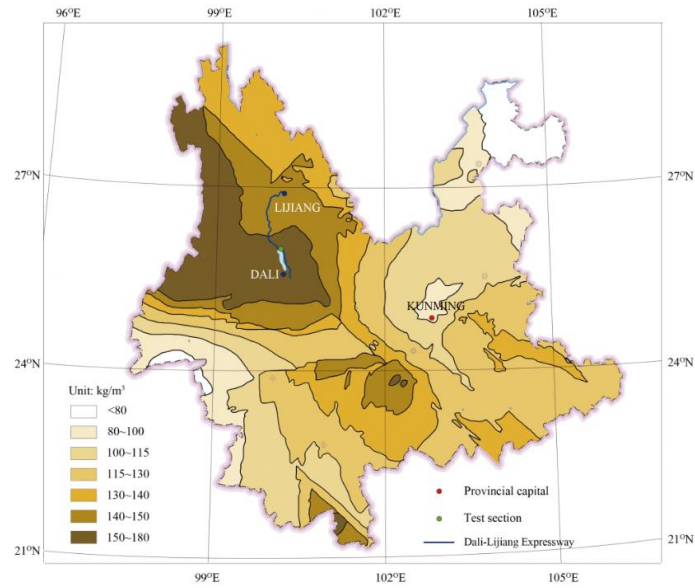


Fig. 2 Dali-Lijiang Expressway and the distribution of organic carbon density in Yunnan (modified after Ma (2013))

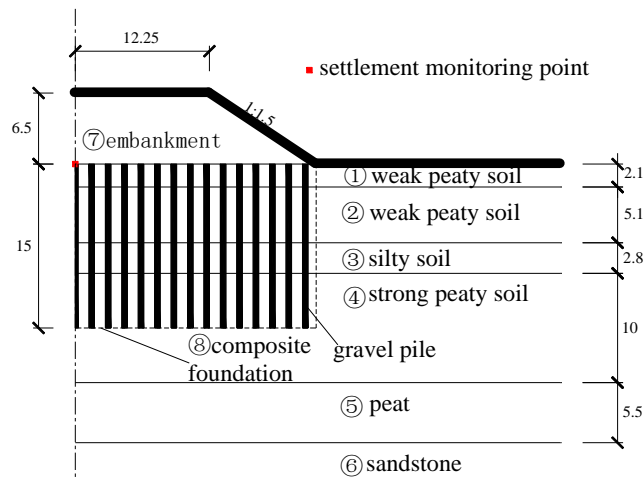


Fig. 3 Schematic half cross-section and geological conditions (unit: m)

height of the embankment is 6.5 m, and the widths of the base and top are 44.33 m and 24.5 m, respectively. The composite foundation consists of soil and gravel piles. The diameter and length of a pile are 0.5 m and 15 m, respectively. The piles are arranged in a square shape, the distance between two adjacent piles being 1.5 m. There is a very thin layer of sand cushion between the base of the embankment and the top of the foundation, which helps the drainage of water from the foundation. Layer 6 comprises sandstones and is considered to be stable and incompressible. Before the construction of the road, the site conditions were investigated and the soil profile was sampled by layer. The samples were obtained from a borehole, and some laboratory tests were conducted to characterize the physical properties of the layers. The results are the average of three parallel samples and are listed in Table 1. The natural unit weight γ , in situ void ratio e_0 , in situ water content w_0 , and organic content w_u of the layers are obtained by sampling and laboratory tests according to *Standard for soil test method* (GB/T 50123-

1999, Ministry of Construction of People's Republic of China 1999). The effective overburden pressure p'_0 was calculated using the initial ground depth and natural soil unit weight. Uniaxial confined consolidation tests were conducted with multi-stage loading (25 kPa→50 kPa→100 kPa→200 kPa→300 kPa→400 kPa), and each stage ended when the strain rate of the sample became less than 0.001 mm/h. The preconsolidation pressure p_c was given by Casagrande method. The obtained preconsolidation pressure of each layer was close to the calculated overburden pressure, which indicates that all the layers were normal consolidated historically. The secondary compression index C_a varies with pressure (Mesri and Ajlouni 2007). In this paper, the values of the secondary compression index from the tests were selected to be consistent with the calculated overburden pressure. For example, the calculated overburden pressure of Layer 1 (weak peaty soil) was 32.4 kPa. Thus, the value of the secondary compression index was selected from the tested data under 25 kPa.

Table 1 Properties of natural peat deposits

Layer no.	Soil type	γ (g/cm ³)	e_0	w_0 (%) ^a	w_u (%) ^b	p'_0 (kPa)	p_c (kPa)	C_c	C_a
1	Weak peaty soil	1.62	1.49	58	16.6	32.4	50	0.55	0.016
2	Weak peaty soil	1.75	1.17	42	15.1	98.32	100	0.38	0.011
3	Silty soil	1.60	1.50	57	9.1	144.97	150	0.45	0.019
4	Strong peaty soil	1.129	4.02	210	52.6	270.39	250	2.34	0.210
5	Peat	1.15	3.19	172	74.9	323.17	300	1.91	0.140

^aDry weight determined at 60-70°C

^bSamples heated to 700°C

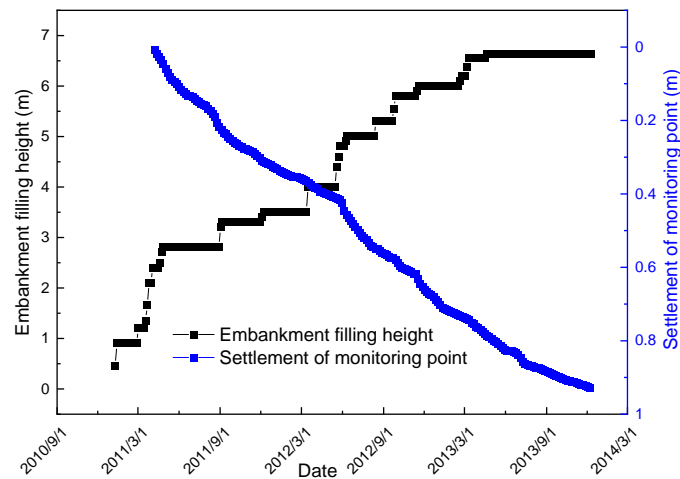


Fig. 4 Embankment filling height and foundation settlement under the center of the express line

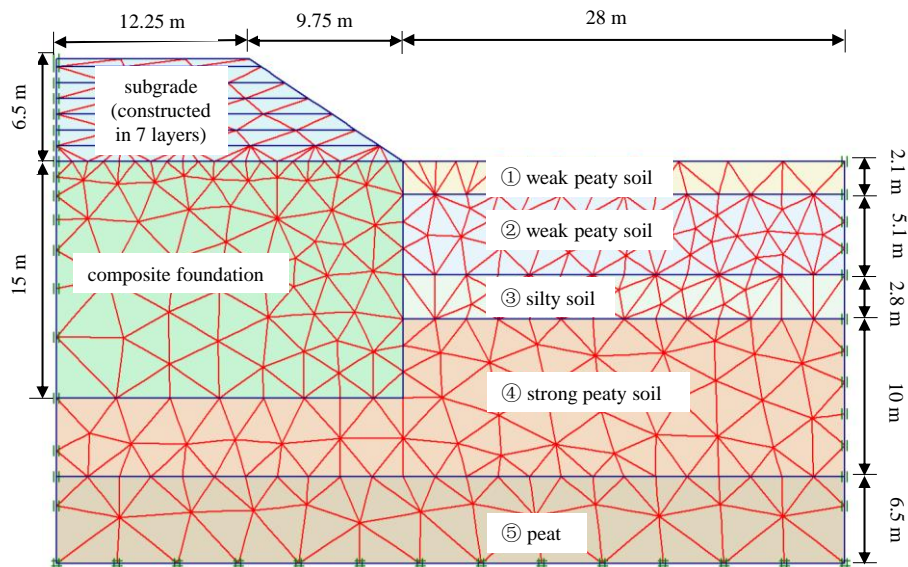


Fig. 5 Numerical model

As shown in Fig. 4, the embankment was constructed from January 1, 2011 to March 7, 2013, while the settlement monitoring was manually conducted through level and total station from April 5, 2011 to November 9, 2013. The filling rate of the embankment was controlled by the limitation posed by the foundation settlement rate as a high settlement rate would cause foundation failure. During

the construction process, the maximum foundation settlement rate was 4.4 mm/d. At the end of the observation period, the foundation settlement was 0.925 m, and the settlement rate was approximately 0.5 mm/d.

2.2 Numerical modeling

2.2.1 Model configuration

A 2D model was built using the finite element modeling program PLAXIS 8.2. As presented in Fig. 5, the studied section is axisymmetric. Thus, a half cross-section model was established according to the site conditions. The model width was 50 m, and the calculated foundation depth was 25.5 m as the stable sandstone layer was located under the peat deposits and was incompressible. The composite foundation was simplified by considering it as a uniform material.

2.2.2 Boundary, initial conditions, and loading process

The vertical boundaries were fixed to prevent horizontal movements, while a pinned boundary was assumed at the base. Closed consolidation was considered for all boundaries except the top boundary of the foundation. The initial pore pressure at the top was 0 kPa. The embankment load increment was 1 m for every 30 d until completion.

2.2.3 Parameters of interest

The expressway profile was modeled using the Mohr–Coulomb model, and the composite foundation and natural organic layers were modeled using SSC model. The permeability change index C_k of the organic layers is defined as the ratio of the change in void ratio to the change in permeability coefficient, and it can be estimated as $C_k=0.25e_0$ (Mesri and Ajlouni 2007). According to SSC model (al-Khoury 2002), the modified compression index λ^* , modified creep index μ^* and modified recompression index κ^* are calculated as follows:

$$\lambda^* = \frac{C_c}{2.3(1+e)} \quad (1)$$

$$\mu^* = \frac{C_a}{2.3(1+e)} \quad (2)$$

$$\kappa^* = \frac{2C_r}{2.3(1+e)} \quad (3)$$

where the recompression index C_r is defined as the ratio of the change in void ratio to the change in the log to the base 10 of effective vertical stress in resilience tests. When the resilience test data are absent, the swelling index of peat soil could also be estimated as seen below (Yu 2015)

$$C_r = 0.1C_c \quad (4)$$

The values of coefficient of permeability k_0 , cohesion force c , and friction angle ϕ of organic layers were obtained from laboratory tests.

For the composite foundation, the parameters were determined by considering a combination of foundation soil and piles. The compression modulus of the composite foundation E_{CS} was calculated as follows:

$$E_{CS} = mE_{PS} + (1-m)E_{SS} \quad (5)$$

where m is the ratio of the pile replacement area, and $m=0.087$ for this case; and E_{PS} and E_{SS} are the compression moduli of the piles and foundation soil, respectively. The compression modulus is defined as the ratio of the change in axial stress to the change in axial strain of a soil sample with lateral confinement. In this

Table 2 Studied parameters of soil containing organic matters (SSC model)

Layer with no.	γ (kN/m ³)	k_0 (cm/s)	C_k	e_0	C_c	C_a	λ^*	κ^*	μ^*	c (kPa)	ϕ (°)
Weak peaty soil 1	15	5×10^{-5}	0.4	1.5	0.55	0.016	0.1	0.012	0.003	34	1
Weak peaty soil 2	15	5×10^{-5}	0.3	1.2	0.38	0.011	0.08	0.013	0.002	20	20
Silty soil 3	16.0	5×10^{-6}	0.8	1.5	0.45	0.019	0.08	0.012	0.002	7	20
Strong peaty soil 4	11	1×10^{-4}	1	4.0	2.34	0.210	0.20	0.037	0.013	22	20
Peat 5	11	1×10^{-4}	0.8	3.2	1.91	0.140	0.20	0.037	0.006	99	7
Composite foundation 8	16.0	1×10^{-3}	0.8	1.5	N/A	N/A	0.05	0.01	0.002	40	20

Table 3 Parameters of interest of materials without organic matters (M-C model)

Material	γ (KN/m ³)	E_s (MPa)	ν	c (kPa)	ϕ (°)
Embankment filling 7	20	30	0.3	50	25

study, E_{PS} and E_{SS} were 19.5 MPa and 1.65 MPa according to the results of laboratory tests, and thus, E_{CS} was calculated to be 3.2 MPa. The compression modulus E_s and modified compression index λ^* are defined as seen below.

$$E_s = \frac{\Delta P}{\Delta \epsilon} \quad (6)$$

$$\lambda^* = \frac{\Delta \epsilon}{\Delta \ln P} \quad (7)$$

where ΔP and $\Delta \epsilon$ are the change in pressure and displacement of the material, respectively. Thus, λ^* could be calculated as

$$\lambda^* = \frac{\Delta P}{E_s \times \Delta \ln P} \quad (8)$$

Eq. (9) is derived from Eqs. (1) and (2), while Eq. (10) is derived from Eqs. (1), (3), and (4).

$$\frac{\lambda^*}{\mu^*} = \frac{C_c}{C_a} \quad (9)$$

$$\frac{\lambda^*}{\kappa^*} = 5 \quad (10)$$

For the composite foundation, the pressure P varied from 100 kPa to 200 kPa considering the overburden soil and factor of safety. Thus λ^* was calculated to be 0.05 using Eq. (8). Accordingly, μ^* and κ^* of the composite foundation were calculated to be 0.002 and 0.01, respectively.

The indexes of the composite parameters of interest for the foundation layers and the composite foundation are summarized in Table 2. The parameters for the embankment filling are summarized in Table 3. The parameters, including γ , k_0 , C_k , e_0 , E_s , C_a , c , and ϕ , listed in Tables 2 and 3 are derived from the accurate or approximate tested value in laboratory through parallel test. While the

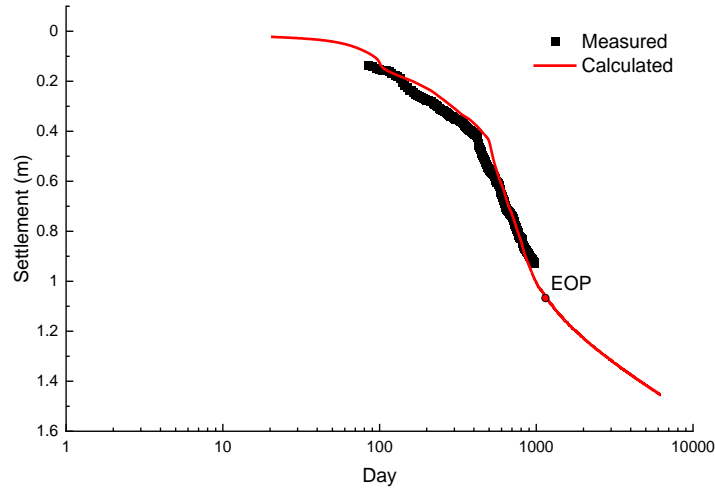


Fig. 6 Comparison between the simulated and monitored settlements of the observation point. EOP denotes end-of-primary settlement

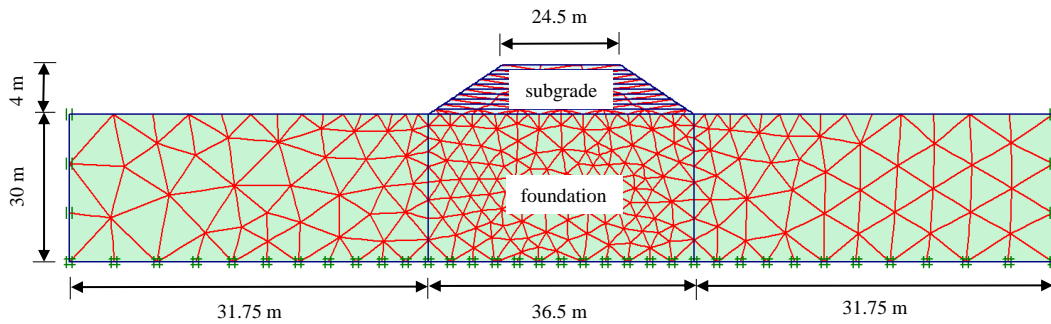


Fig. 7 Numerical model used for verification of the SSC model

parameters ν , C_c , λ^* , κ^* , and μ^* are calculated or estimated values.

2.3 Verification of numerical simulation

According to *Technical Standard of Highway Engineering* (JTG-B01-2014, Ministry of Transport of the People's Republic of China 2015), the design service life of an expressway with a bituminous concrete pavement is 15 yr. Thus, the simulation period starts from the beginning of construction and ends at 15 yr post-construction. Figure 6 depicts the simulated settlement of the centerline of the foundation surface during this period. At the end of field observation period, the simulated settlement is 1.03 m and close to the measured settlement 0.925 m. The simulated results are in good agreement with the measured results during the observation period. Fifteen years later after the construction, the calculated settlement is 1.46 m and the rate is 10.92 mm/yr. Due to the requirement from the local transport office, observed data after 2013 are unavailable. However, the observed data before 2013 shows that the primary consolidation of the foundation was nearly completed at the end of observation period. Besides, the consolidation settlement of soil comprises the drainage of pore water and the creep of soil. The creep of soil is the main cause of the secondary compression, but also occurs in the primary compression stage of soil, although it has a

minor influence on the primary settlement in comparison with the drainage of pore water. Thus, the good fit of the calculated settlement to the measured settlement in the primary compression stage suggests the validity of the numerical simulation.

As shown in Fig. 6, after 1085 d from the beginning of construction, the primary compression ends. The calculated settlement of the centerline of the foundation surface is 1 m. At the end of the simulation period, the calculated settlement is 1.45 m, and the proportion of secondary settlement is 31%.

3. Numerical simulation of peat soil foundation consolidation settlement based on the SSC model

3.1 Simulation conditions and parameters of interest

According to the comparison between the measured and calculated data in Section 2, the SSC model and PLAXIS 8.2 software are proved to be effective in the assessment of the settlement of organic-matter-laden foundation subjected to embankment load. In this section, a numerical model of a foundation subjected to the embankment load is built, and the parameters of 17 types of organic-matter-laden soils are assigned to the model separately in order to study the relationship between physical parameters and settlement.

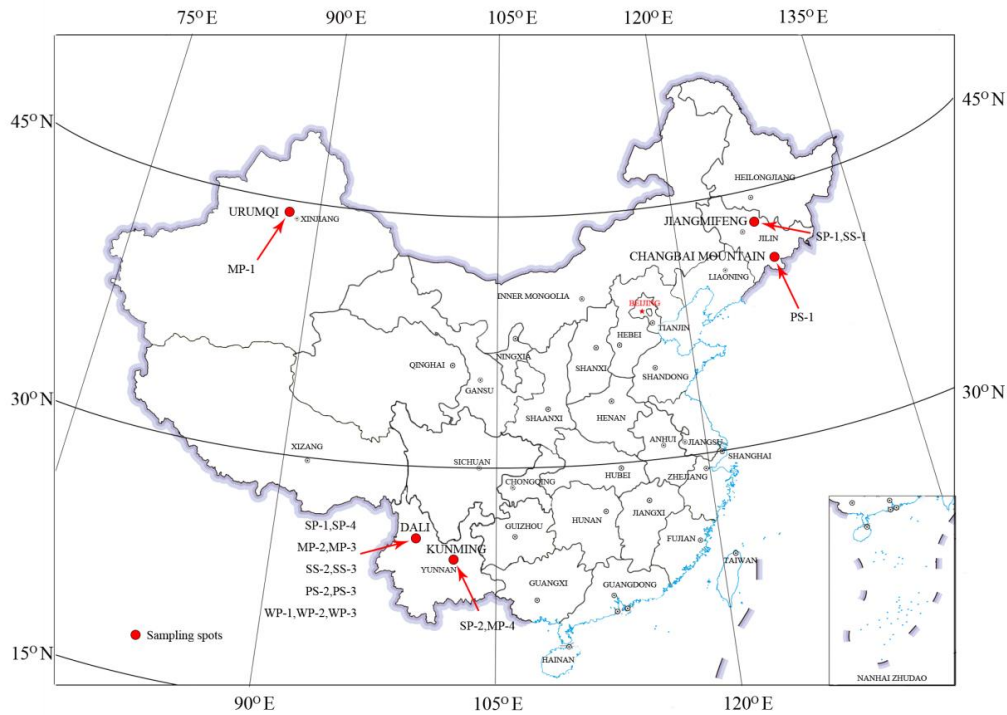


Fig. 8 Map showing selection of soils from different regions of China for the computational test

Table 4 Studied parameters of materials with organic contents

Material	Source	w_u (%)	γ (kN/m ³)	k_0 (cm/s)	C_k	e_0	C_c	C_a	λ^*	κ^*	μ^*	E_s (MPa)	c (kPa)	ϕ (°)
SS-1	Li (2006)	1.1	18.5	1×10^{-6}	0.3	0.7	0.24	0.001	0.05	0.01	0.0002	2.89	17	17
SS-2	Xiong (2005)	7.5	16.7	5×10^{-6}	0.6	1.4	0.22	0.01	0.04	0.008	0.002	3.62	16	15
SS-3	This paper	9.1	16	5×10^{-6}	0.7	1.5	0.45	0.019	0.07	0.012	0.003	1.46	7	10
WP-1	This paper	15.1	15	1×10^{-5}	0.3	1.2	0.38	0.011	0.08	0.013	0.002	2.87	20	20
WP-2	This paper	16.6	15	1×10^{-5}	0.4	1.5	0.55	0.016	0.1	0.02	0.003	1.86	34	1
WP-3	Yu (2015)	16.8	14	1×10^{-5}	0.6	2.3	0.85	0.051	0.11	0.02	0.006	1.3	9	2
MP-1	Feng <i>et al.</i> (2016)	26.4	13.3	1.2×10^{-4}	0.4	1.6	0.37	0.02	0.06	0.012	0.004	2.58	45	25
MP-2	Liu (2014)	33.02	13.1	3×10^{-5}	0.5	2	0.66	0.04	0.1	0.02	0.005	1.49	16	16
MP-3	Huang (1999)	35.9	12.5	3×10^{-5}	0.7	2.7	1.12	0.067	0.12	0.024	0.007	1.1	12	10
MP-4	Jiang (1994)	39.5	12.2	3×10^{-5}	1.1	4.6	1.22	0.073	0.09	0.018	0.005	1.52	10	7
SP-1	Jiang (1994)	41.84	12.7	1×10^{-4}	0.9	3.4	1.43	0.086	0.14	0.028	0.008	1.06	16	16
SP-2	Jiang (1994)	42.2	13	1×10^{-4}	0.9	3.7	1.42	0.085	0.13	0.027	0.008	1.1	13	10
SP-3	Li (2006)	50.5	11.2	1×10^{-4}	0.9	2.5	1.43	0.024	0.14	0.028	0.004	1.34	13	15
SP-4	This paper	52.6	11.3	1×10^{-4}	1	4	2.34	0.17	0.2	0.04	0.012	1.42	22	20
PS-1	Xu (2008)	61.1	10.3	1×10^{-4}	2.1	8.3	4.89	0.294	0.23	0.046	0.011	0.63	25	15
PS-2	Jiang (1994)	65	11	1×10^{-4}	1.2	4.9	2.72	0.163	0.2	0.04	0.009	0.72	18	22
PS-3	This paper	74.9	11.5	1×10^{-4}	0.8	3.2	1.91	0.048	0.2	0.04	0.007	2.28	99	7

Note: SS, silty soil; WP, weak peaty soil; MP, medium peaty soil; SP, strong peaty soil; PS, peat

As shown in Fig. 7, the width of the embankment top is 24.5 m, and the embankment height is 4 m. The calculated width and depth of the foundation are 100 m and 30 m, respectively. The movement of the base is fixed in all

directions, and the bottom boundary drains freely. The side boundaries are fixed to avoid horizontal movement but they are free in terms of vertical movements. The side boundaries also drain freely. The embankment element is

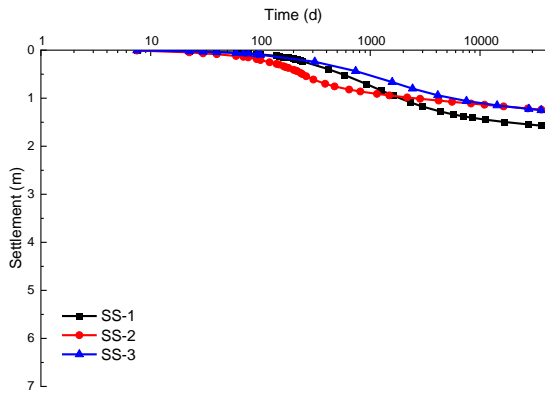


Fig. 9 Variation in settlement of silty soil foundations

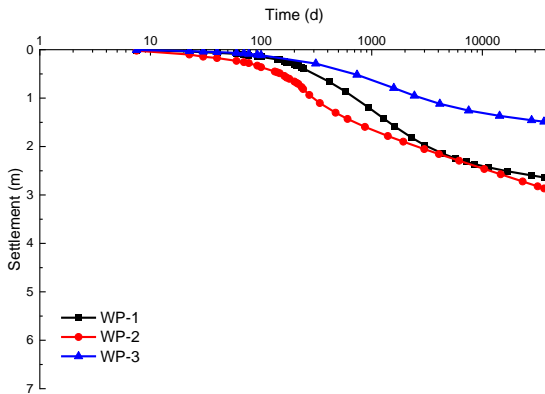


Fig. 10 Variation in settlement of weak peaty soil foundations

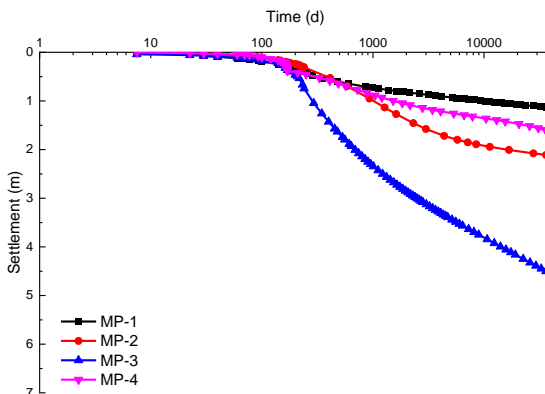


Fig. 11 Variation in settlement of medium peaty soil foundation

divided into four 1 m thick layers to simulate the step-by-step construction of embankment, and the embankment accumulates 1 layer every 30 d until the embankment construction is finished. The embankment filling is modeled using the Mohr-Coulomb model. For the embankment filling, the unit weight, compression modulus, Poisson ratio, cohesion, and friction angle are 20 kN/m³, 30 MPa, 0.35, 50 kPa, and 25°, respectively.

Fig. 8 shows the sources of 17 selected organic-matter-laden soils in China. Their physical parameters, which are listed in Table 4, are assigned to the numerical model separately. It is noted that the organic contents in these soils range from 1.1-74.9%, which covers a wide range of

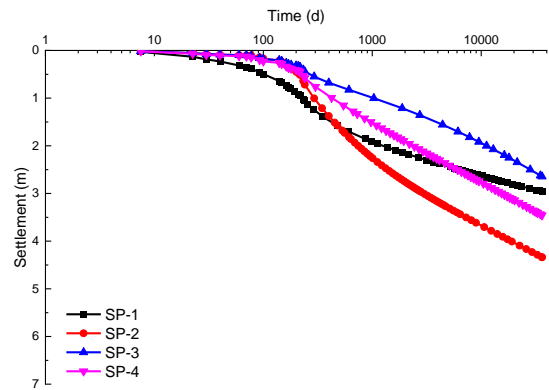


Fig. 12 Variation in settlement of strong peaty soil foundations

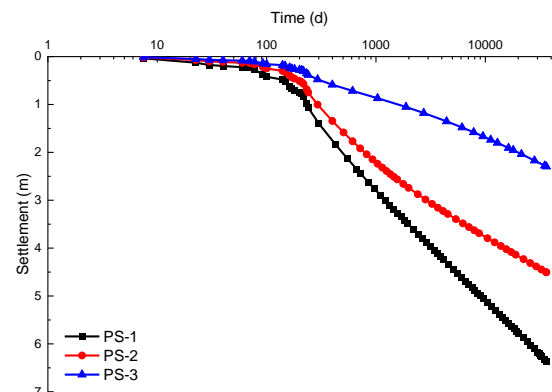


Fig. 13 Variation in settlement of peat foundations

natural organic-matter-laden soils.

3.2 Results and analysis

As shown in Figs. 9-13, for most foundation materials, the settlements occur in the first 5000 d, and the settlement rates of different foundations rapidly decrease after construction. Figs. 14 and 15 show the calculated results of the final settlement and its rate. One hundred years after construction, the PS-1 foundation experienced the highest settlement of 6.358 m, with a settlement rate of 10.25 mm/yr, whereas the settlements and settlement rates of most other foundations ranged from 1-5 m and 1-6 mm/yr, respectively.

Fig. 14 shows that the total foundation settlement generally increases with organic content. The total settlements for silty soil, weak peaty soil, medium peaty soil, strong peaty soil, and peat foundation range from 1000-2000, 1500-3000, 1000-5000, 2500-4500, and 2000-6500 mm, respectively. Organic matters in soil are characterized by high void ratios and compressibility. Besides, organic matters would be lost/degraded and fragmented at the later stage of consolidation. The loss of organic matters would be induced by the seepage, drainage, and degradation by microorganism. Subjected to the degradation by microorganisms and external load, organic matters would possess a lower strength and be even fragmented. An increase in organic content increases both the primary settlement and the secondary settlement.

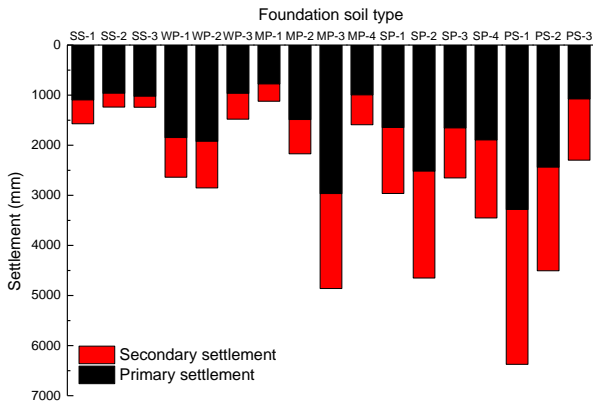


Fig. 14 Calculated settlements of different foundations

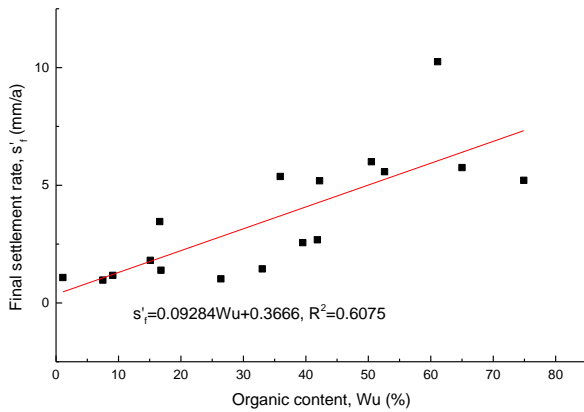


Fig. 15 Relation between organic content and final settlement rate

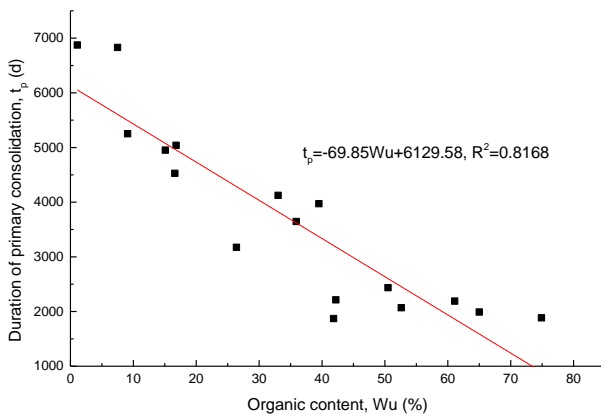


Fig. 16 Relation between organic content and duration of primary consolidation

As shown in Fig. 16, the duration of primary consolidation decreases with increasing organic content before the organic content reaches 40%. For silty soil foundations and weak peaty soil foundations, the durations of primary consolidation range from 5000-7000 d because of the small pores and weak permeability. For strong peaty soil foundations and peat soil foundations (with 40% organic content or higher), the durations of primary consolidation are approximately 2000 d.

In Fig. 17, the proportions of secondary settlement in total settlement of silty soil, weak peaty soil, medium peaty

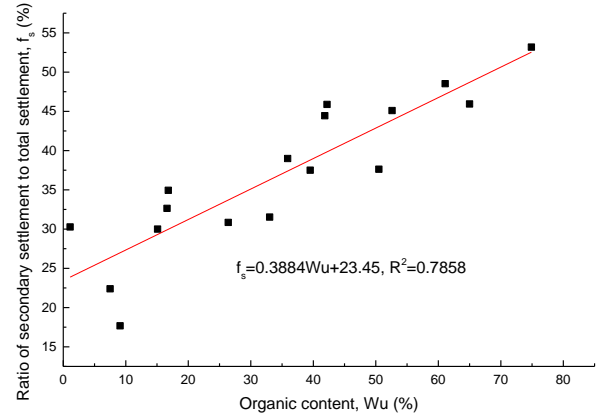


Fig. 17 Relation between organic content and ratio of secondary settlement to total settlement

soil, strong peaty soil, and peat soil foundations are 17-30, 30-35, 30-40, 37-46, and 45-53%, respectively. The proportion of secondary settlement u_s in total settlement u increases with increasing organic content, indicating that the compression of organic matter contributes to the end result to a greater extent than the compression of pores. Thus, the secondary settlement significantly affects the total settlement and should not be ignored in engineering practice.

4. Prediction model of peat soil foundation based on multiple linear regression

4.1 Statistical analysis

The calculated data were further analyzed using the multiple linear regression method with the statistical software SPSS (version 23). Natural unit weight, permeability, compression index, secondary compression index, cohesion, and friction angle were selected as the dependent variables to begin with, while the total settlement and secondary settlement were selected as the independent variables. Analysis of variance (ANOVA) was conducted to determine the significances of the regressions and parameters. The dependent variables were reassessed according to the results of the ANOVA. The results predicted by the regressions and finite element models were then compared to validate the regressions.

4.2 Consolidation settlement prediction model

Peat deposits are characterized by high water content and compressibility. Subjected to embankment loads, peat soil foundations become compressed, and their settlement threatens the structural integrity of the embankment. In order to propose an empirical model to predict the total settlement u and secondary settlement u_s of peat soil foundations using multiple linear regression, the selected calculated results and relative parameters of the peat soil foundation settlements are summarized in Table 5. Some of the variables were sourced from previous studies (Fox *et al.* 1994, Gui *et al.* 2016, Mesri *et al.* 1997).

Table 5 Selected independent variables and dependent variables in the prediction models

Material	γ (KN/m ³)	k_0 (cm/s)	e_0	C_c	C_α	c (kPa)	φ (°)	u (m)	u_s (m)
SS-1	18.5	1×10^{-6}	0.7	0.24	0.001	17	17	1.57	0.48
SS-2	16.7	5×10^{-6}	1.4	0.22	0.01	16	15	1.237	0.28
WP-1	15	1×10^{-5}	1.2	0.38	0.011	20	20	2.637	0.79
WP-2	15	1×10^{-5}	1.5	0.55	0.016	34	1	2.852	0.93
MP-1	13.3	1.2×10^{-4}	1.6	0.37	0.02	45	25	1.12	0.35
MP-2	13.1	3×10^{-5}	2	0.66	0.04	16	16	2.17	0.68
MP-3	12.5	3×10^{-5}	2.7	1.12	0.067	12	10	4.86	1.9
SP-1	12.7	1×10^{-4}	3.4	1.43	0.086	16	16	2.963	1.32
SP-2	13	1×10^{-4}	3.7	1.42	0.085	13	10	4.65	2.13
SP-3	11.2	1×10^{-4}	2.5	1.43	0.024	13	15	2.651	1
SP-4	11.3	1×10^{-4}	4	2.34	0.17	22	20	3.451	1.56
PS-1	10.3	1×10^{-4}	8.3	4.89	0.294	25	15	6.373	3.09
PS-2	9.2	1×10^{-4}	4.9	2.72	0.163	18	22	4.506	2.07
PS-3	11.5	1×10^{-4}	3.2	1.91	0.048	99	7	2.297	1.22

Table 6 ANOVA of u regression model (11)

	Sum of squares	Degrees of freedom	Mean square deviation	F	Significance α
Regression	26.344	6	3.763	8.532	0.009
Residual	2.647	7	0.441	-	-
Sum	28.991	13	-	-	-

Table 7 Significance analysis for model (11)

Parameter	Coefficient		t	Significance α
	b_i	Standard error		
Constant	6.447	2.789	2.511	0.046
x_1 γ	-0.224	0.167	-0.342	0.228
x_2 k_0	-5533.3	8802.739	-0.038	0.971
x_4 C_c	1.646	0.851	3.800	0.011
x_5 C_α	2.755	9.486	3.201	0.018
x_6 c	-0.9	0.032	-2.741	0.023
x_7 φ	-0.002	0.046	-2.632	0.039

4.2.1 Total consolidation settlement prediction model

The total settlement u is the dependent variable. The independent variables, namely unit weight, initial coefficient of permeability, initial void ratio, compression index, secondary compression index, cohesion, and friction angle are represented by x_1 , x_2 , x_3 , x_4 , x_5 , x_6 , and x_7 , respectively. The initial void ratio has a linear correlation with the compression index (Sridharan and Nagaraj 2001), and thus, x_3 was eliminated from the multiple linear analysis. The calculations according to the multiple linear analysis are summarized in Tables 9 and 10, and the initial regression of u is expressed as follows:

$$u=6.447-0.224\gamma-5533.3k_0+1.646C_c+2.755C_\alpha-0.9c-0.002\varphi, R^2=0.909, S_e=0.66415 \quad (11)$$

Table 8 ANOVA of u regression (12)

	Sum of squares	Degrees of freedom	Mean square deviation	F	Significance α
Regression	22.261	4	5.565	7.442	0.006
Residual	6.730	9	0.748		
Sum	28.991	13			

Table 9 Significance analysis of model (12)

		Coefficient		t	Significance α
		b_i	Standard error		
Constant		4.039	0.998	2.511	0.009
x_4	C_c	0.551	0.870	3.800	0.011
x_5	C_α	11.328	28.456	3.201	0.018
x_6	c	-0.054	0.037	-2.666	0.029
x_7	φ	-0.037	0.050	-2.554	0.034

Table 10 Verification of the empirical model (12)

Sample	Dependent variable				u (m)		
	C_c	C_α	c	φ	Numerical value (simulated)	Empirical value (calculated)	Error
PS-1	4.9197	0.14976841	25	15	6.373	6.541	0.168
PS-2	2.714	0.0768798	18	22	4.506	4.619	0.113
MP-1	0.3588	0.01250096	45	25	1.120	1.023	0.097

Table 6 shows that the value of the significance α is 0.009 (< 0.05), which indicates that a significant linear correlation exists between the independent and dependent variables. Next, the significances of the partial regression coefficients are validated and summarized in Table 7. The significances of the initial coefficient of permeability and natural unit weight are 0.971 and 0.228, respectively. As both values are higher than 0.1, the results indicate no significant linear correlation with the total settlement. Thus, the initial coefficient of permeability and natural unit weight should be eliminated in further analysis to obtain a modified prediction model. The calculations are summarized in Tables 8 and 9, and the modified regression is expressed as follows:

$$u=4.039+0.551C_c+11.328C_\alpha-0.054c-0.037\varphi, R^2=0.806, S_e=0.6585 \quad (12)$$

As shown in Table 8, the regression significance α is lower than 0.05, which indicates a significant linear correlation between the independent and dependent variables. In Table 9, the significances of all the dependent variables are lower than 0.05.

Three types of soils were selected to verify model Eq. (12), and the verification results are provided in Table 10. The total settlement calculated by this empirical model is close to the result calculated by the numerical model. For a given foundation thickness, embankment height, and construction process, the total settlement shows positive linear correlations with the compression index and secondary compression index, and negative linear correlations with the cohesion and friction angle. The unit

Table 11 ANOVA of us regression model (13)

	Sum of squares	Degrees of freedom	Mean square deviation	F	Significance α
Regression	7.411	5	1.482	12.041	0.001
Residual	0.985	8	0.123		
Sum	8.396	13			

Table 12 Significance analysis of model (13)

	Coefficient		t	Significance α
	b_i	Standard error		
Constant	1.275	0.998	3.879	0.005
x_2 k_0	3325.355	3046.746	3.201	0.018
x_4 C_c	0.551	0.870	2.880	0.013
x_5 C_α	11.328	28.456	2.511	0.009
x_6 c	-0.054	0.037	-2.268	0.053
x_7 φ	-0.037	0.050	-2.239	0.056

Table 13 Verification of model (13)

Sample	Independent variable					u_s (m)		Error (m)
	k_0 (cm/s)	C_c	C_α	c	φ	Numerical (simulated) value	Empirical model (calculated) value	
WP-2	0.00001	0.55	0.016	34	1	0.931	0.798	-0.133
MP-1	0.0001	0.37	0.02	45	25	0.345	0.462	+0.117
SP-1	0.001	1.43	0.086	16	16	1.317	1.363	+0.046

weight and initial coefficient of permeability show a low linear correlation with the total settlement. As the total settlement corresponds to a stable consolidated state that the foundation finally reaches after a long period, the initial coefficient of permeability, which represents the draining velocity, has little influence on the total settlement. The variation in the unit weight of the natural foundation soil is relatively small compared with the embankment load, and the variation thus shows no significant influence on the total settlement.

4.2.2 Secondary settlement prediction model

Secondary settlement significantly influences the total settlement. Thus, a prediction model for secondary settlement should also be established. Using multiple linear analysis, the calculations are summarized in Tables 11 and 12, and the regression is expressed as follows:

$$u_s = 1.275 + 0.309C_c + 6.174C_\alpha - 0.04c - 0.011\varphi + 3325.355k_0 \quad (13)$$

Table 13 shows that the empirical model predicts the secondary settlement of foundations with organic matters quite satisfactorily. The compression index, secondary compression index, and initial permeability have positive correlations with the secondary settlement, whereas the cohesion and friction angle show negative correlations with it. Compared with the total settlement, the secondary compression lasts longer and contributes to the settlement to a greater extent as the initial permeability increases.

5. Conclusions

Peat soils are widely distributed all over China. The strong compressibility of peat soils threatens the performance of structures and buildings on peatlands and has caused many problems. In this study, the SSC model was validated through the comparison between numerical simulation and field observation of an organic-matter-laden foundation of a test section in Dali-Lijiang expressway. Subsequently, we developed a numerical model of expressway which employs the SSC model, and the parameters of 17 types of selected organic-matter-laden soils were assigned to the model separately. According to the calculated results of the numerical simulation, two empirical models were proposed using multiple linear regression to predict the total settlement and secondary settlement of the peat soil foundations. The following are the conclusions of this study:

- The SSC model can be used to predict the settlement of foundations containing organic matters. Based on the calculated results of numerical simulation employing the SSC model and 17 types of organic-matter-laden soils, two empirical models are established using multiple linear regression to simply and rapidly assess the total and secondary settlement of organic-matter-laden foundation subjected to embankment load. Further countermeasures could be suggested based on the assessed primary and secondary settlement.

- The settlement characteristics generally have good linear relationships with the organic matters, although local fluctuations still exist because of variations in other factors. Under the same computational conditions, an increase in the organic content of the foundation soil typically decreases the duration of primary consolidation and increases the final settlement rate and secondary settlement. The proportions of secondary settlement in the total settlement of silty soil, weak peaty soil, middle peaty soil, strong peaty soil, and peat soil foundations were found to be 17-30, 30-35, 30-40, 37-46, and 45-53%, respectively.

- For a given computational condition, the total foundation settlement shows positive linear correlations with the compression index and secondary compression index, and negative linear correlations with the cohesion and friction angle. The secondary settlement of the foundation follows similar laws, but the secondary settlement also exhibits a positive linear correlation with the initial coefficient of permeability.

- The results of laboratory consolidation test show that the undisturbed soil samples from the test section have a potential of long-term and large settlement. According to the field observation in the test section of Dali-Lijiang expressway, the rate of settlement remained significant at the end of construction. It indicates that the composite foundation, which installs gravel piles in natural foundation, shows limited ability in settlement control of organic-matter-laden foundation. Thus, more effective ways to lower the settlement rate and final settlement of the peat deposits should be studied and tested in the future.

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