Acta Technica *61*, No. 4A/2016, 95–108

Stability control and consolidation sedimentation analysis on soft soil foundation subjected to surcharge preloading treatment

Canbin Yin[1], Min Wang[2]

Abstract. A method for controlling the treatment construction stability of several types of soft soil foundations is proposed, according to field measured data in combination with a Wuhan-Yingshan highway soft soil foundation treatment project case. The method is capable of more effectively controlling the stability of foundations during the construction process in combination with a sedimentation rate control method stipulated by standards. ABAQUS applies an expanded D-P model based on the creep rule and the consolidation theory to perform simulation numerical calculation on the project case, and a sedimentation calculation result of numerical simulation is compared with on-site measured sedimentation. By virtue of the contrast analysis on three consolidation degree calculation methods, namely inverse calculation on pore water pressure, sedimentation calculation and the consolidation theoretical calculation, and in combination with numerical analysis results, sedimentation inverse calculation comparison is performed, so that the method has certain guiding significance in researching consolidation degrees and sedimentation rules of roadbeds.

Key words. Soft soil foundation, stability, consolidation degree, ABAQUS, sedimentation analysis.

1. Introduction

As for a state that the foundations have relatively thick soft soil layers, surcharge preloading is performed on a soft soil roadbed by use of drainage systems such as a sand well or a plastic drainage plate and the like. Research on the stability control and roadbed sedimentation rules during a roadbed construction process has always been the hotspot in an existing soft soil foundation treatment technology, a stability control method stipulated by standards only considers the influence of the sedimentation rate on the roadbed stability, a more comprehensive and practical stability

---

[1] Hunan City University, Hunan, 413000, China

[2] Construction Project Quality Safety Supervisory Station, Hunan, 413400, China

control method still needs further research and demonstration, and research on soft soil consolidation sedimentation rules is undergoing development. In recent years, a method for solving problems such as foundation deformation of roadbeds and constructions through applying analysis software and a finite element method on the predecessors' consolidation theory of predecessors by scholars at home and abroad has been extensively applied, so that development of the consolidation theory is greatly promoted. However, problems such as mutual relations among soft soil secondary consolidation-creep property analysis, soil solidification-creep coupling theory, soil sedimentation-consolidation degree and pore water pressure change remain to be further researched and improved.

In overall consideration of the above several problems, the paper provides several methods for controlling the roadbed stability during a construction process by virtue of construction on-site supervision on soft soil foundation treatment, in which one year and two months were spent, of the typical roadbed section K59+710 and comprehensive analysis on monitoring data under a project background of the soft soil roadbed test section of the Wuhan-Yingshan highway. Numerical simulation is performed by use of ABAQUS, key technical indexes such as roadbed sedimentation and consolidation degree are analyzed, so that the methods have relatively practical significance in guiding project construction and researching soft soil sedimentation rules.

2. Project profile

Main sections of the whole Wuhan-Yingshan highway have staggered bridges and soft soil foundations, and a considerable number of the main sections are bridgehead regions with relatively thick soft soils and relatively high bridgehead embankment filling height, so that problems of roadbed instability and uneven sedimentation at connection parts of the bridgeheads and embankments would be certainly caused. Furthermore, the influence of huge high-filled lateral pressure on the structure is unignorable especially for bridge abutment pile foundations which obliquely cross with the highway, if this problem is mishandled, the structure safety would be surely and seriously influenced. On this account, in combination with accumulated experience [1–2] in soft soil foundation treatment in recent years, a preloading method is adopted to treat soft soil foundations, roadbed filling construction is performed according to a thin turning method, a soft soil foundation monitoring system is established, and Table 1 is a partial data table including various indexes of project on-site construction monitoring.

3. Research on roadbed filling stability control method

According to requirements in the Highway Soft Soil Foundation Embankment Design and Construction Technique Standards [3], when the embankment reaches a limit equilibrium state, the embankment stability control standards are as follows: the sedimentation rate V of a single day is less than or equal to 15 mm/d, and the lateral displacement rate V_{c} is less than or equal to 5.0 mm/d. Although such a stability control method is universally applied to construction processes, judgment only based on the sedimentation rate for different construction situations is biased. In many project cases [4], a roadbed instability problem also occurs under a situation that the sedimentation rates meet standard requirements. In order to guide construction more scientifically and specifically, the paper hereafter analyzes and discusses the roadbed stability according to the construction monitoring data of the Wuhan–Yingshan highway and provides several new stability control methods.

Table 1. In-situ test data table

Actual filling height (m)	2.33	2.55	2.73	3.06	3.84	4.43	5.38	6.35
Actual accumulated load (kPa)	44.27	48.45	51.87	58.14	72.96	84.17	102.22	120.65
Maximal lateral displacement rate V_{c} (mm/d)	0	0.14	0.41	0.3	0.8	0.63	0.09	0.08
Accumulated lateral displacement rate $\sum V_{\mathrm{c}}$ (mm/d)	0	0.14	0.55	0.85	2.75	3.38	4.12	4.2
Accumulated lateral extrusion amount V_{h} (mm^3)	0	325	600	562	3500	6150	16912.5	17900
Maximal sedimentation rate V (mm/d)	2.60	0.80	3.33	1.50	2.24	4.43	0.89	1.69
Accumulated sedimentation rate $\sum V$ (mm/d)	2.60	3.40	7.73	9.23	16.41	20.84	23.30	24.99
Accumulated displacement $\delta 3.5$ (mm)	0	0.55	1.1	1.7	7.8	11.3	32.3	34.1
Accumulated sedimentation s (mm)	16.00	23.00	38.00	44.00	119.00	174.90	269.15	368.40
$\triangle u 3.5$	0.00	0.55	0.55	0.92	0.09	0.11	0.82	0.52
$\sum \triangle u 3.5$	0.00	0.55	1.10	2.02	2.22	2.33	3.15	3.67

3.1. Analysis of pore water pressure increase

By real-time monitoring on the pore water pressure during a roadbed filling process, it is easy to discover that changes of the pore water pressure undergo an "increase-dissipation-stabilization" process during each filled soil loading process. The dependence of $\sum u$ on $\sum \triangle P$ obtained from measurement results of pore water pressures in different depths is shown in Fig. 1. As shown in the figure, the curve of each section is linear during the initial stage of filling, and the slope of each curve decreases in the later stage of filling, which indicates that the foundation consolidation degree at the later stage increases, the foundation strength increases, and the foundation tends to be stable. During the whole filling process, the curve in each section has flex points at the earlier stage of filling. The paper analyzes the physical significance corresponding to the first flex point of each section. In Fig. 1, the first flex point position occurs at the fourth-stage filled load (the corresponding filling height is 3.84 m), i.e., when the filling height is up to 3.84 m, the curve is still relatively straight; when the next-stage load is filled, the curve turns upwards with increased slope. According to elastoplasticity theoretical analysis of soils, when the filling height is up to 3.84 m, the soil reaches the plastic deformation stage. Therefore, the corresponding filling height which ensures that the soils are converted into the plastic stage from an elastic stage is about 3.84 m, which is approximately the limit filling height obtained by theoretical calculation. The above analysis shows that within the limit filling height, the curve is linear, and the foundation soils are in the elastic stage, so that loading can be accelerated at the moment. After the filling height exceeds the limit filling height, the curve has an upward flex point, and the foundation soils are in the plastic deformation stage, so that the loading rate can be slowed down, and loading is further performed after the foundation soils achieve the required consolidation degree. During the loading process, when the curve has an upward flex point, i.e., the slope of curve increases, the foundation might become unstable, and a loading stop measure or an unloading measure should be taken. Therefore, whether the foundation is stable or not can be judged according to the slope change of the curve, so as to guide the filling rate.

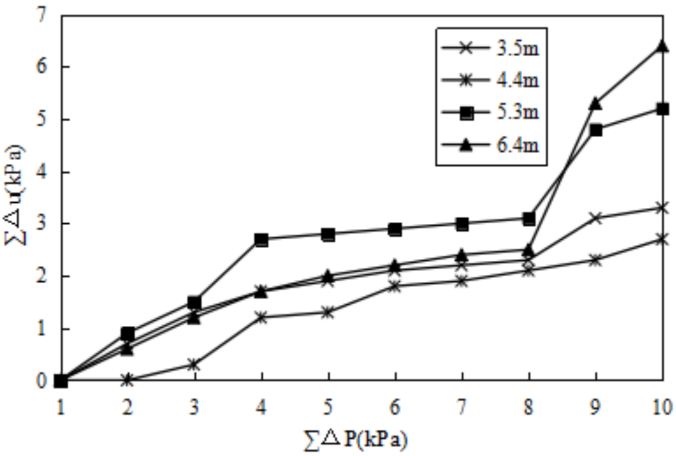

Fig. 1. Dependence of $\sum u$ on $\sum \triangle P$ in different depths

3.2. Flex point analysis method

In practical engineering application, after data processing is performed on instantaneous sedimentation quantity caused by loading of each stage, the displacement rate and pore pressure increase caused by loading of each stage implied by soil non-drainage deformation can be disclosed. The deformation stage and stability of soils can be judged by virtue of a comprehensive analysis.

Japanese Tominaga and Hashimoto pointed out that: when the ratio of the lateral displacement of the loading slope to the sedimentation quantity S of the loaded middle part increases sharply, it means that the foundation is nearly damaged (see the left graph of Fig. 2). When the preloading load is relatively small, the curve should have an included angle θ with S, and the measuring point moves along the line E. Finally, when the preloading load approaches the failure load, the increase is more obvious than increase of S as shown in I and II in the left graph of Fig .2.

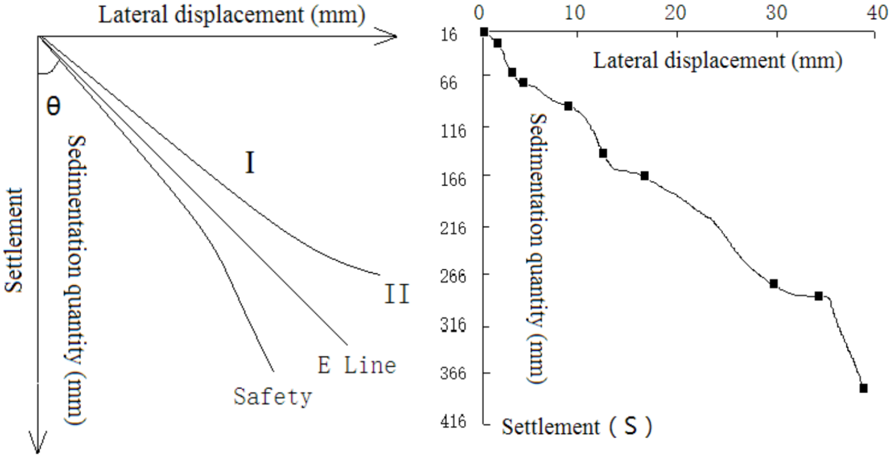

Fig. 2. Relation of lateral displacement and sedimentation quantity

4. Finite element simulation on consolidation sedimentation of soft soil roadbed

4.1. Selection of constitutive model of soil

Aiming at soil used as a special project material [5, 6], ABAQUS provides common elastic-plastic constitutive models [7] such as a modified Cambridge model, an expanded Drucker–Prager model and a Mohr–Coulomb model. As a further expansion of a modified Drucker–Prager model, the expanded Drucker–Prager model in the ABAQUS takes influence of a deviatoric stress invariant J3 into consideration. It is configured with the corresponding creep rule and consolidation theory and can well reflect the nonlinear characteristic of the soil material, so that the expanded Drucker–Prager model is extensively adopted in actual project calculation and can be used for calculating the deformation problem of soft soils, especially the rheological problem. The paper adopts the expanded Drucker–Prager model to perform relevant numerical calculation.

4.2. Determination of model parameters

The soil layer of the foundation in the test section of the Wuhan–Yingshan highway is divided into the first layer consisting of loam, second layer consisting of muddy clay, third layer again consisting of loam, fourth layer consisting of sludge and fifth layer consisting of fine sand. The fifth layer serves as a bottommost layer in the calculations. According to routine soil test results, specific physical and mechanical property indexes of each layer are shown in Table 2.

Table 2. Physical and mechanical properties of particular soil layers

Soil layer	1	2	3	4	5
Thickness (m)	0.9	3.0	2.2	0.6	13.2
Water content (%)	37.24	31.38	28.98	32.24	25.30
Density (N/cm^3)	14.3	15.5	13.7	14.7	14.9
Void ratio	0.903	0.762	0.863	0.838	0.817
Plastic limit	23.1	25.2	22.4	24.31	18.6
Liquid limit	38.6	45.5	36.7	40.15	34.0
Compressibility coefficient	0.545	0.496	0.384	0.356	0.328
Consolidation coefficient	1.54	1.21	1.10	1.66	0.525
Osmotic coefficient	4.48E–8	2.89E–8	1.78E–7	5.25E–8	2.40E–8
Fast shear - c	12	22	0	38	23
Fast shear - φ	27.0	23.1	31.0	15.5	11.5

A creep model [6], [8–11] corresponding to creep in the ABAQUS is capable of enlarging the use range of the Drucker–Prager model and solving complicated creep problems, especially a soft soil creep problem. Furthermore, the common Mohr–Coulomb model parameters can be obtained from a rheological test report and they can be converted into Drucker–Prager model parameters using the following equations.

When in associated flow $\psi = \beta$ (ψ representing the expansion angle on the p–w surface), then

$$\tan\beta = \frac{\sqrt{3}\sin\phi}{\sqrt{1+\frac{1}{3}\sin^2\phi}}\,, \tag{1}$$

$$\frac{d}{c} = \frac{\sqrt{3}\cos\phi}{\sqrt{1+\frac{1}{3}\sin^2\phi}}\,. \tag{2}$$

When no volume expansion exists ($\psi = 0$), then

$$\tan \beta = \sqrt{3} \sin \phi \,, \tag{3}$$

$$\frac{d}{c} = \sqrt{3} \cos \phi \,, \tag{4}$$

and

$$\sigma_{\mathrm{c}}^{0} = \frac{1}{1 - \frac{1}{3} \tan \beta} \,, \tag{5}$$

where σ_{c}^{0} represents the initial yield stress.

According to rheological test results of the test section and conversion relation between the Drucker–Prager model parameters and Mohr–Coulomb model parameters, specific model parameters are shown in Table 3.

Table 3. Calculation parameters for finite element analysis

Soil layer	β	σ_{c} (kPa)	K	A	n	m
1	33.595	45.464	0.8187	4E-7	6	0
2	43	9.4	0.8715	1E-7	0.7	0
3	21.595	86.398	0.8834	4E-7	6	0
4	38.174	44.276	0.7927	8E-7	5.5	0
5	30.401	99.95	0.8364	4E-7	6	0

Here, A, n and m are three parameters for the time hardening criterion of the expanded Drucker–Prager model. In the initial stage of creep, the influence of creep parameter changes on soil deformation is not quite remarkable; however, excess pore water pressure gradually dissipates over time, so that the influence of excess pore water pressure on deformation is also gradually weakened, and the influence of the creep parameter plays a leading role. If the influence of the creep parameter m on creep development is relatively less and since the creep parameter m is not less than -1 and not greater than 0, the influence of the creep parameter m can be ignored in calculation, i.e., m is equal to 0.

4.3. Calculation conditions

The calculation grid is shown in Fig. 3. Two side surfaces are characterized by axial symmetry constraint in direction x, the bottom surface exhibits restraints in both directions x and y, and the ground serves as a boundary with excess pore water pressure equal to 0. Coupled plane strain elements CPE8RP are adopted as soil units. According to exploration data, the bottom of the foundation is set as a non-drainage fixed boundary. In consideration of symmetry, the symmetry plane of the roadbed is set as a non-drainage boundary with horizontal restraint; the right boundary of the calculation section can be set as a non-drainage fixed boundary since it is far enough from the center of the roadbed.

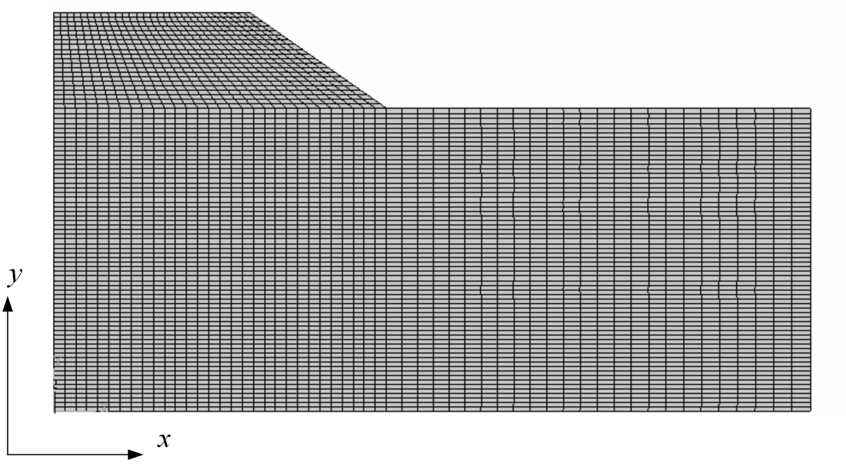

Fig. 3. Finite element grid of the roadbed

5. Analysis of calculation results

5.1. Sedimentation analysis

Results calculated by the expanded Drucker–Prager model considering the creep rules conform to measured values. According to Fig. 4, it can clearly be observed that certain rheological deformation exists in the preloading period, and this conforms to actual project situations; furthermore, numerical calculation results show that a finite element model and selected parameters are basically reasonable. According to the curve, since filling construction is simplified by the finite element model simulation, each simplified single layer is relatively thick in filling thickness. This is caused by relatively high sedimentation rate and relatively high instantaneous sedimentation of the roadbed during the filling period, which indicates that instantaneous sedimentation is relevant to the filling rate. Along with decrease of the later construction rate, the sedimentation rate of the foundation also decreases. After filling construction is finished, the sedimentation quantity and sedimentation rate of the roadbed decreases obviously; and the sedimentation quantity is basically stable about six months after construction.

5.2. Analysis on pore water pressure

The time dependence of pore water pressure in soft soils at different depths in a preloading reinforcement region for plastic drainage plates calculated by applying ABAQUS is shown in Fig. 5.

Figure 5 contains the time dependencies of pore water pressures in foundation soils at different positions below the middle line of the roadbed. Since the figure output by ABAQUS has no unit display, this paper introduces the units in Fig. 5 as

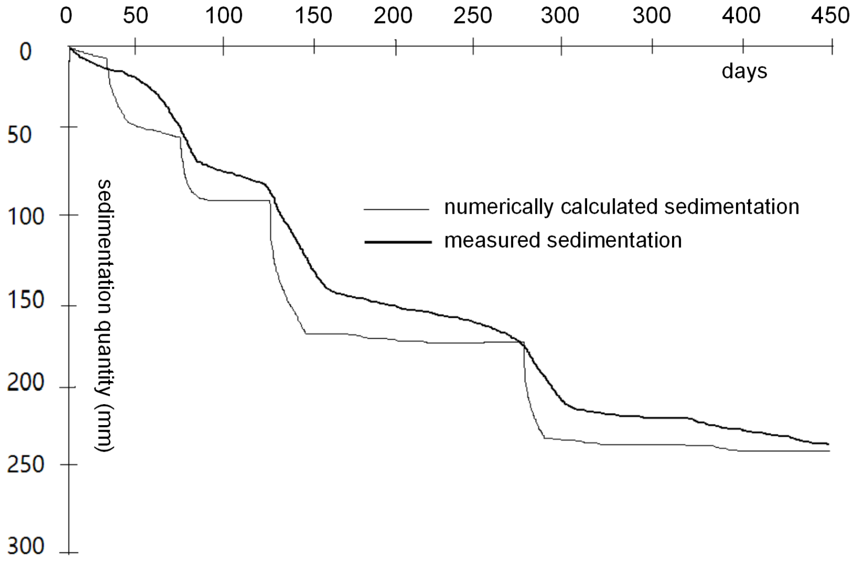

Fig. 4. Comparison of numerical calculation and measured sedimentation

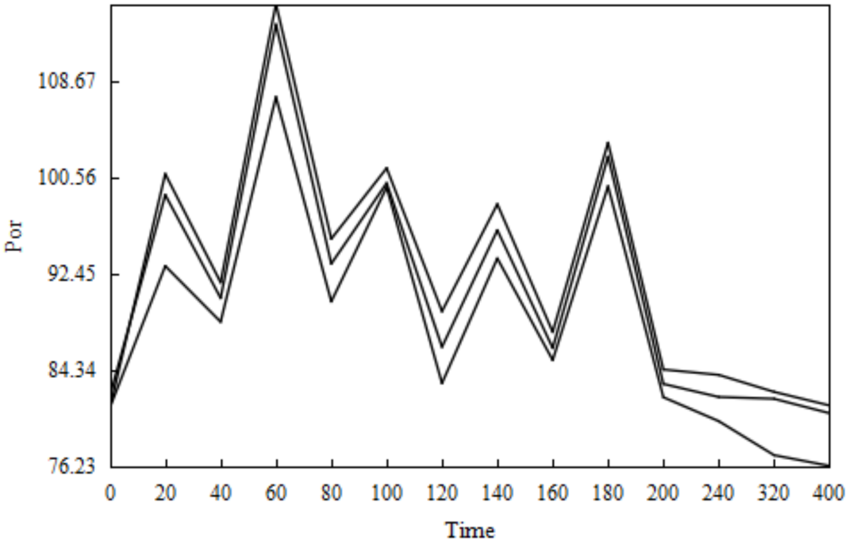

Fig. 5. Time dependencies of pore water pressures at different depths (5 m, 5.5 m and 6 m) of the roadbed

follows: axis Time is a time axis with the unit of one day, while axis Por is the pore water pressure with the unit of kPa. According to the figure, it can be observed that the pore water pressures from once loading to next loading undergo an "increase-dissipation-decrease-dissipation" process, which shows that additional total stress is constantly converted into the effective stress of soil. The soil consolidation process is obvious, the pore pressure dissipation rate is relatively high at the beginning of dissipation, but decreases over time and the pore pressure at the later stage tends to be stable. It can be observed that the consolidation degree further increases, and the foundation gradually reaches a stable state. The consolidation degree of the soft soil roadbed can be obtained from the dissipation situations of pore water pressures at different depths calculated by ABAQUS; by virtue of calculation, the consolidation degree of the soft soil roadbed is 93.87 % for 180 days after the preloading is realized, and it conforms to the theoretical calculation result and the measured result, thus proving that the selected parameters are relatively accurate and a basis is provided for analyzing the consolidation degree and sedimentation below.

5.3. Consolidation degree comparison and sedimentation back calculation

According to the Terzaghi's tree-dimensional consolidation theory [12], the average total consolidation degree of the soil layers in a sand well foundation is caused by combined action of radial average consolidation degree and vertical average consolidation degree. The expression for the average total consolidation degree U_{rz} is [12–14]

$$U_{rz} = 1 - (1 - U_r)(1 - U_z)\,. \tag{6}$$

Considering the Barron solution from 1948 [15] (without taking into account the consolidation coefficient changes in the soil consolidation process) we obtain

$$U_{rz} = 1 - \frac{8}{\pi^2}\mathrm{e}^{\beta t}\,, \tag{7}$$

where

$$\beta = \frac{\pi^2}{4}\cdot\frac{C_{\mathrm{v}}}{H^2} + \frac{8}{F(n)}\cdot\frac{C_{\mathrm{r}}}{d_{\mathrm{e}}^2}\,.$$

Theoretical calculation can be performed on the consolidation degree of soft oils in this project according to the above theoretical equations and in combination with soft soil parameters in the following table. If an H value of 7 m is taken, β is equal to 0.0036, the consolidation degree of soil layers in the soft soil foundation on the four hundredth day is calculated. Then U_r is equal to 91.5 %, U_z is equal to 21.3 % and U_{rz} is equal to 93.3 %.

Figure 6 is a consolidation degree comparison analysis figure. According to the figure, the consolidation degree calculated by use of the consolidation theory is basically approximate to that measured according to sedimentation or pore pressure, so that it indicates that the consolidation degree theoretical calculation is reasonable in parameter selection, and the pore pressure and sedimentation observation results are accurate and are in mutual corroboration. In contrast, the consolidation degree obtained by sedimentation measurement is more approximate to that obtained by theoretical calculation, this is mainly due to the fact that the measurement of excess pore water pressure mainly depends on the underground static level, whereas, the underground static level changes along with time and climate, so that measurement of the underground static level is quite difficult. When the consolidation degree of the test section is calculated according to the pore pressure, hydrostatic pressure changes are not taken into consideration, i.e., the hydrostatic pressure is assumed to be invariant.

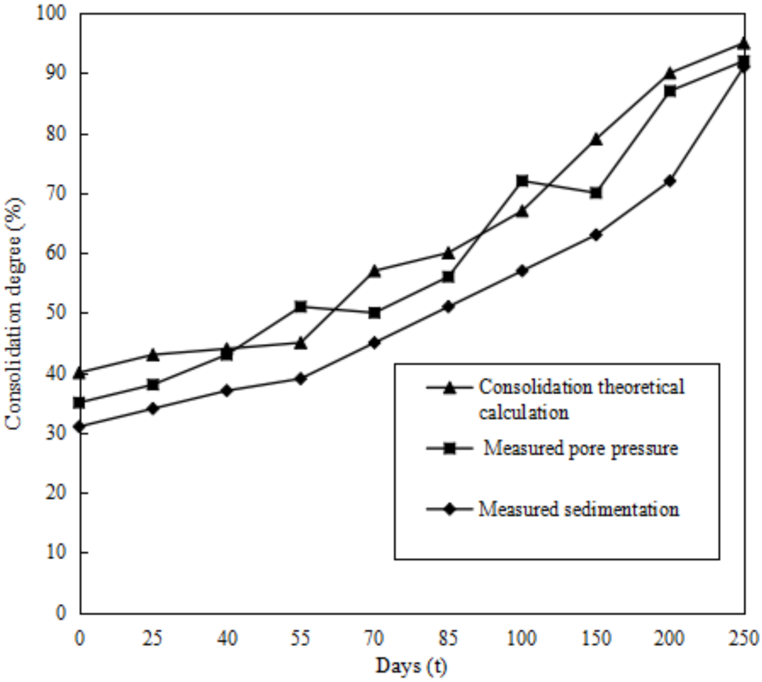

Fig. 6. Comparison of various calculated consolidation degree results

Through comparing the consolidation degree obtained by theoretical calculation with the measured consolidation degree, we can discover that although the consolidation degree obtained by theoretical calculation is less than the measured consolidation degree in the loading period or the earlier stage of preloading, and it is greater than the measured consolidation degree at the later stage of preloading (three months after preloading), thereby indicating that the consolidation coefficient constantly decreases along with increase of time and consolidation degree after soil is preloaded. Through comparing geotechnical tests before and after foundation treatment, the measurement results also prove this inference. This is because during the earlier stage of loading, the soil has relatively large pores, the pore pressure dissipates rapidly and the effective stress of soil increases rapidly, so that the consolidation of soil is relatively rapid, i.e., the consolidation coefficient is relatively large. Along with gradual compression of soil, the void ratio of soil becomes smaller and smaller, the pore pressure dissipation rate becomes lower and lower, and the effective stress increases slowly, so that the consolidation is slower and slower, i.e., the consolidation coefficient becomes smaller.

According to definition of the consolidation degree, one point (t_1, s_1) taken from the measured sedimentation curve is utilized to calculate

$$U(t) = \frac{s_t - s_1}{s_\infty - s_1}\,, \tag{8}$$

where s_1 is the sedimentation quantity of the roadbed at the time t, and s_∞ is the final sedimentation quantity of the roadbed.

Any point taken from the sedimentation curve is utilized to perform reverse-reasoning calculation, and the final sedimentation quantity is 0.456 m. The consolidation degrees of the soft soil roadbed, which are calculated by different methods, are respectively utilized to calculate the final sedimentation quantity of the roadbed, and the results are shown in Table 4.

Table 1. Comparison of final sedimentation quantity calculated by different methods

Consolidation degree calculation method	Soft soil consolidation degree (%)	Final sedimentation quantity of roadbed (m)	Measured sedimentation quantity (m)
Three-dimensional consolidation theory	93.3	0.456	0.454
Measured pore water pressure	92.1	0.465	
ABAQUS numerical calculation	93.8	0.440	

The results shown in Table 4 indicate that the consolidation degree calculated according to the measured pore water pressure is slightly less than the result calculated by ABAQUS. This is because the pore water pressure changes caused by weather and underground water are not considered during the simulation performed by ABAQUS. In actual project, the pore water pressure is influenced by the above factors, so that the consolidation degree calculated according to the measured pore water pressure is smaller. The result of numerical simulation result conforms to the theoretical calculation, which further indicates that the model parameter selection is reasonable, and final sedimentation quantity calculation conforms to the measured sedimentation quantity. This lays foundations for research of the relation between preloading height of the filled soil and preloading time and post-construction sedimentation of the roadbed.

6. Conclusion and outlooks

1. By use of methods such as measured pore water pressure increase monitoring and flex point analysis in a construction process and in combination with judgment based on standard requirements, the method provided by the paper

better conforms to actual project situations, and construction can be better guided.

2. The expanded Drucker-Prager model considering the creep rules is adopted by ABAQUS and takes the influence of rheology on sedimentation into consideration, the calculation results are approximate to the measured results, construction situations are simulated more truly, and a foundation is laid for more follow-up research.

3. The final sedimentation quantity of the foundation, which inversely calculated by use of the consolidation degree, conforms to the calculation result of ABAQUS and the measured sedimentation quantity, thus indicating that a method for calculating roadbed sedimentation by use of theories and numerical values is practical.

4. In analysis calculation of sedimentation and stability of the soft soil foundation, selected soil parameters conforming to actual situations have great influence on analysis results. In future research, how to select a more suitable soil constitutive model and perform inversion to obtain accurate soil property parameters on the basis of measured data has great research significance and practical value.

References

[1] H. Sabetamal, M. Nazem, S. W. Sloan, J. P. Carter: *Frictionless contact formulation for dynamic analysis of nonlinear saturated porous media based on the mortar method.* IJ Numerical and Analytical Methods in Geomechanics *40* (2016), No. 1, 25 to 61.

[2] J. P. Carter, H. Sabetamal, M. Nazem, S. W. Sloan: *One-dimensional test problems for dynamic consolidation.* Acta Geotechnica *10* (2015), No. 1, 173–178.

[3] X. Zhang, D. Sheng, S. W. Sloan, K. Krabbenhoft: *Second-order cone programming formulation for consolidation analysis of saturated porous media.* Computational Mechanics *58* (2016), No. 1, 29–43.

[4] V. V. Orekhov: *Analysis of interaction between structures and saturated soil beds subject to static and seismic effects.* Soil Mechanics & Foundation Engineering *52* (2015), No. 2, 68–73.

[5] B. K. Low: *Practical probabilistic slope stability analysis.* Subsurface Drainage for Slope Stabilization *2* (2003), No. 4, 2777–2784.

[6] M. Lu, S. Wang, S. W. Sloan, B. Indraratna, K. Xie: *Nonlinear radial consolidation of vertical drains under a general time-variable loading.* IJ Numerical and Analytical Methods in Geomechanics *39*, (2015), No. 1, 51–62.

[7] G. Chen, Z. Zhou, H. Pan, T. Sun, X. Li: *The influence of undrained cyclic loading patterns and consolidation states on the deformation features of saturated fine sand over a wide strain range.* Engineering Geology *204* (2016), 77–93.

[8] B. Indraratna, C. Rujikiatkamjorn, A. S. Balasubramaniam: *Ground improvement at the Port of Brisbane, Australia using vertical drains and vacuum assisted preloading.* Sound Geotechnical Research to Practice: Honoring Robert D. Holtz II (2013), 539–549.

[9] N. J. JIANG, Y. J. DU, S. Y. LIU, M. L. WEI, P. S. HORPIBULSUK: *Multi-scale laboratory evaluation of the physical, mechanical, and microstructural properties of soft highway subgrade soil stabilized with calcium carbide residue.* Canadian Geotechnical Journal *53* (2015), No. 3, 373–383.

[10] Z. ZHANG, M. HUANG: *Geotechnical influence on existing subway tunnels induced by multiline tunneling in Shanghai soft soil.* Computers and Geotechnics *56* (2014), No. 3, 121–132.

[11] Z. CHEN, H. ZHU, Z. YAN, L. ZHAO, Y. SHEN, A. MISRA: *Experimental study on physical properties of soft soil after high temperature exposure.* Engineering Geology *204* (2016), 14–22.

[12] H. LIU, C. ZHENG, X. DING, H. QIN: *Vertical dynamic response of a pipe pile in saturated soil layer.* Computers and Geotechnics *61* (2014), 57–66.

[13] C. ZHENG, H. LIU, X. DING, Y. LV: *Torsional dynamic response of a large-diameter pipe pile in viscoelastic saturated soil.* IJ Numerical and Analytical Methods in Geomechanics *38* (2014), No. 16, 1724–1743.

[14] L. LI, L. WU, X. WANG, Z. CUI: *Seismic response of underground structures in saturated soil based on the fluid-solid coupling dynamic formulation.* J Coastal Research *73* (2015), Suppl. 1, 432–435.

[15] R. A. BARRON: *Consolidation of fine grained soil by drain well.* Geotechnical Special Publication *74* (1948), No. 118, 324–360.

Received November 16, 2016