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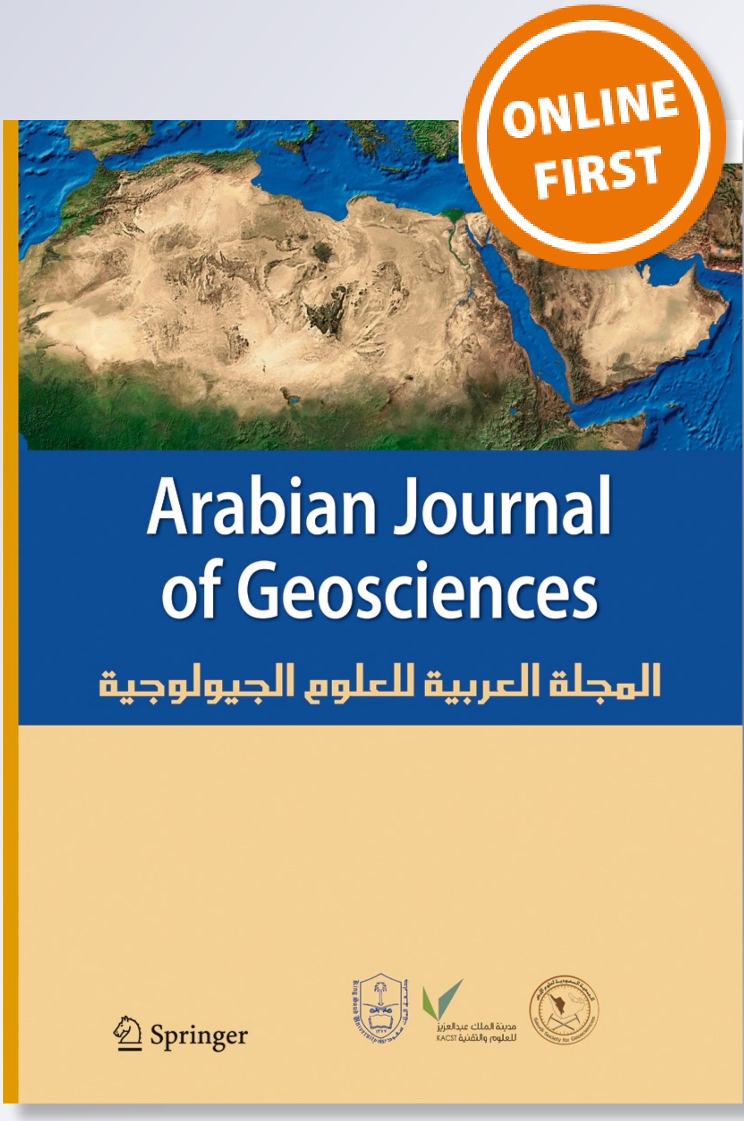

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ORIGINAL PAPER

Effects of embankment height and vehicle loads on traffic-load-induced cumulative settlement of soft clay subsoil

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Abstract In order to study the traffic-load-induced cumulative settlement of soft clay subsoil under the low embankment, in situ tests are carried out, and based on the undrained cumulative deformation model and cumulative pore pressure model of Shanghai soft clay proposed by Huang and Li, the cumulative settlement was calculated and analyzed. The calculated cumulative settlement agrees well with the measured result. The cumulative settlement is mainly caused by the undrained cumulative deformation and the pore-pressure-dissipation-induced consolidation deformation, and the former is major. The effects of the embankment height and vehicle loads on traffic-load-induced cumulative settlement are studied. For the embankment less than 1.5 m high, the cumulative settlement of subsoil quickly increases with the decrease of the embankment height. The greater the vehicle loads, the more rapidly the cumulative settlement grows. When the vehicle loads rise by 20 % than the standard, the cumulative settlement increases by 44 %. Therefore, limiting the vehicle overload is critical to control the cumulative settlement. Considering the effects of road embankment height and vehicle loads, the model for predicting cumulative settlement is put forward.

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Introduction

In China, the high embankment more than 4 m had been widely adopted in road construction, but they occupied a great amount of farmland. Therefore, in some cities and regions, the high grade roads with a low embankment were designed and constructed. Shanghai Municipal Engineering Design Institute attempted to design the western section of Shenfengjin expressway, of which the average embankment height was about 1.2 m. The decrease of the embankment height reduces the settlement of subsoil induced by the self-weight of the embankment. However, the dynamic stress induced by the repeated traffic loads can cause large cumulative settlement of the soft layer of subsoil under the low embankment. Since the 1950s, this phenomenon has drawn great attention from engineers. Fujikawa and Miura (1996) studied the airport expressway with a low embankment in Saga and found that the traffic-load-induced settlement was about 400~600 mm, which accounted for about 50 % of the total settlement, and was a relatively large settlement in contrast to the allowable settlement for highways. Based on field measurement at the Beizhai intersection of the Outer-ring line in Shanghai, Ling et al. (2002) found that the cumulative settlement of pavement attained to 90~100 mm. He (2005) showed that the traffic-load-induced settlement of Chinese Shenzhen-Shantou expressway was about 300 mm, though the subsoil was treated with the surcharge preloading method. Therefore, studying traffic-load-induced cumulative settlement of subsoil is extremely significant.

Researches about traffic-load-induced cumulative settlement of soft subsoil were mainly concentrated on cumulative deformation models of soft clay and cumulative pore pressure models. It can be summarized as two research methods: one is complicated constitutive model of soft clay established to simulate each load cycle; the other one is the empirical fitting method. Mroz et al. (1979) employed an anisotropic hardening model to analyze the elastoplastic deformation soils. Liang and Ma (1992) studied the undrained cyclic behavior of clay with an anisotropic plasticity model. Wang and Yao (1996) and Zhong et al. (2002) employed the kinematic hardening multi-yield surface model and isotropic elastoplastic boundary surface model to simulate cumulative residual deformation of soft clay under undrained condition. When the number of calculating cycles is large, the computation is quite time consuming, so this method is difficult to be applied to practical engineering. In the empirical fitting method, the relationships of the residual deformation of soil with initial consolidation characteristics, static stress state, dynamic stress, and the number of cycles are established. A simple exponential model was proposed by Monismith et al. (1975) to reflect the relationship between the cumulative strain and the number of cycles, but there were great differences between the calculated results and the measured ones. Considering the effects of types and physical states of soil, Li and Selig (1996) introduced static strength of soil to the Monismith model. Taking the effect of the dynamic deviatoric stress of soil into account, Chai and Miura (2002) modified the Li-Selig model and put forward a new exponential empirical model to predict traffic-load-induced settlement of soft clay subsoil under a low embankment. In addition, based on the results of the laboratory triaxial tests, many researchers (Hyodo et al. 1992; Jiang and Chen 2001; Sakai et al. 2003) analyzed residual deformation characteristics of soft clay. Cui et al. (2014) carried out in situ tests to study cumulative settlement of silt subsoil in the Yellow River delta. Huang et al. (2006) performed a series of undrained cyclic triaxial tests on typical Shanghai soft clay, and based on the concept of critical state soil mechanics, an undrained cyclic cumulative deformation model and a cumulative pore pressure model of saturated soft clay were proposed. With these two models, undrained cumulative settlement of soft clay can be calculated, and through combining with consolidation theory, consolidation settlement induced by the dissipation of cumulative pore pressure also can be obtained at the same time.

The road embankment height and vehicle load are two important factors affecting cumulative settlement of the low embankment, and they determine vehicle-load-induced dynamic stress in subsoil. In the Chinese design specifications of road, the vehicle loads are regarded as equivalent uniform static loads applied on the pavement to analyze the stability of embankment, but the dynamic effect of vehicle load on the cumulative settlement of subsoil is not considered. Meanwhile, engineers are also concerned with the effect of the embankment height on traffic-load-induced cumulative settlement, but there is little correlative research. In this study, in situ tests are carried out, and based on the undrained cumulative deformation model and cumulative pore pressure model of Shanghai soft clay proposed by Huang and Li, the cumulative settlements are calculated, and the effects of road embankment height and vehicle loads on the cumulative settlements are analyzed.

In situ tests of cumulative settlement

Description of the site

The test site is located in the Beizhai section of the Outer-ring road line in Shanghai city which is bidirectional four lanes. The Beizhai section of the Outer-ring road was opened to traffic on January 10 in 1999. Referring to the Chinese Specifications for the Design of Highway Asphalt Pavement (JTG D50-2004), the traffic spectrum can be converted into the standard vehicle load. Based on the same effect on the pavement, various vehicle loads were converted into the standard vehicle load of 200 kN. Statistics showed that the traffic volume of standard vehicle for a single lane of the Outer-ring line was about 1,500 times a day, so it was taken as daily vehicle load numbers in the following calculation of cumulative settlement.

The subsoil in this area is typical saturated soft clay. Groundwater is 0.5 m below the ground surface. In order to monitor the cumulative settlements of subsoil, two layered settlement gauges were arranged at two locations of the Beizhai section, as shown in Fig. 1. These two monitoring points are set in the center of the roadway, and their distance is about 12 m. The cumulative settlements of soft clay subsoil during 2.5 years after opening to traffic were monitored at the site. The mechanics parameters of soft subsoil, subgrade, and pavement structure are shown in Table 1. In Table 1, φ_{cu} and c_{cu} are consolidated undrained internal frictional angle and

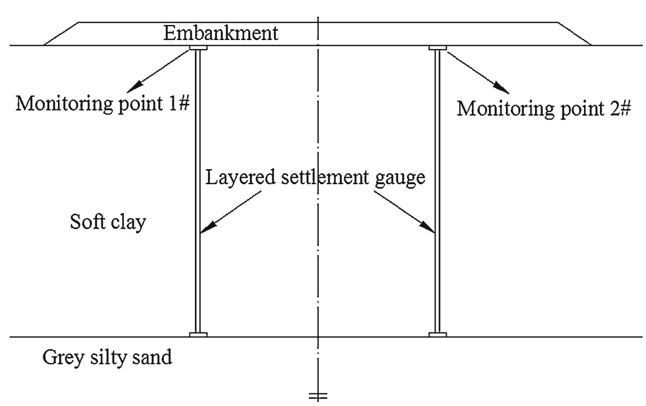

Fig. 1 Layered settlement gauges layout

Table 1 Mechanics parameters of pavement structure, subgrade, and subsoil

Soil type	Thickness (m)	Compression modulus (MPa)	Unit weight (kN/m^3)	Poisson ratio	φ_{cu} (°)	c_{cu} (kPa)	K_0	Permeability coefficient (m/s)
Asphalt concrete pavement	0.15	1,200	22	0.2	–	–	–	–
Lime-fly ash stabilized aggregate base	0.4	1,400	20	0.2	–	–	–	–
Soil-lime subbase	0.3	60	20	0.2	–	–	–	–
Plain fill subgrade	1.0	18	18	0.25	–	–	–	–
Soft clay	17	2.9	17.8	0.3	19.0	7.0	0.67	7.11×10^{-10}
Gray silty sand	12	11.2	19.4	0.25	23.0	7.0	0.61	4.02×10^{-7}

cohesion of soil, and K_0 is the coefficient of earth pressure at rest. The soft clay layer is the main compressible stratum.

In situ test results

Figure 2 shows the variation curves of the measured cumulative settlement with time after opening to traffic. It can be found that the cumulative settlement grows quickly initially, but the speed of increase becomes gradually slower. The measured cumulative settlements of these two monitoring points have not much difference. After opening to traffic for 2.5 years, the average traffic-load-induced cumulative attains to about 104 mm. The large settlement leads to many down-top cracks on the pavement.

Calculation of cumulative settlement

Cumulative deformation model of soft clay under cyclic loads

Under cyclic loads, the cumulative deformation of undrained soft clay is related to the number of cyclic loads, soil characteristics, stress history, and so on. The constitutive model of soft clay under cyclic loads in previous researches mostly was exponential model proposed by Monismith et al. (1975):

$$\varepsilon_p = A \times N^b \tag{1}$$

where ε_p is the cumulative plastic strain; N is the number of cyclic loads; b is a constant; A is the first cyclic-load-induced cumulative deformation ε_1.

The study of Chai and Miura (2002) demonstrates that ε_1 is a function of confining pressure p_c, static deviatoric stress q_s, and dynamic deviatoric stress q_d. In order to describe the position of stress point of the loading path in the undrained cyclic tests, Huang et al. (2006) introduce deviatoric stress level:

$$D = q/q_{ult} \tag{2}$$

where D is the deviatoric stress level; q is deviatoric stress, $q=\sigma_1-\sigma_3$, σ_1 is the maximum principal stress, and σ_3 is the minimum principal stress; q_{ult} is the undrained failure strength which can be derived by employing modified Cam-Clay constitutive model theory:

$$q_{ult} = \left(\frac{1}{2}\right)^{1-\frac{\kappa}{\lambda}} M p_c \tag{3}$$

where p_c is the confining pressure which is equal to preconsolidation pressure; λ and κ are the slope of the normal consolidation line and the rebound curve in e-lg$p$ space, e is void ratio of soil and p is vertical stress in the confined compression test; M is the slope of the critical state line of modified Cam-Clay constitutive model. For the Shanghai soft clay, κ=0.03, λ=0.13, M=1.49.

Referring to Eq. (2), D_s and D_d are defined as the static deviatoric stress level and the peak dynamic deviatoric stress level, respectively: $D_s=q_s/q_{ult}$ and $D_d=q_d/q_{ult}$. Considering the effects of D_s and D_d, relative deviatoric stress level D^* is presented:

$$D^* = \frac{D_d - D_s}{1 - D_s} \tag{4}$$

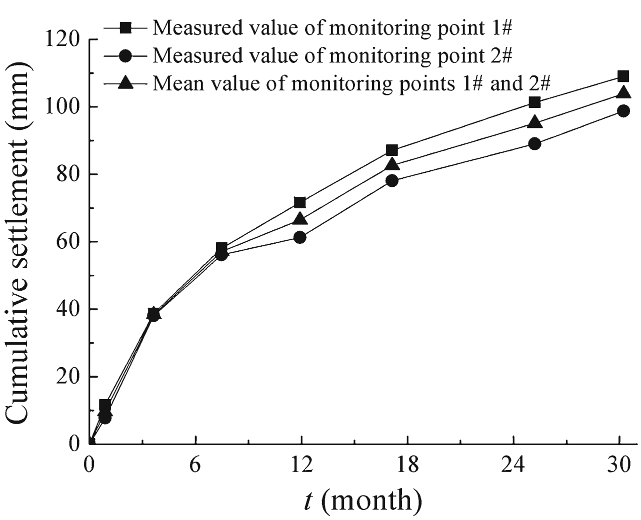

Fig. 2 Development of the measured cumulative settlement with time after opening to traffic

Huang et al. (2006) found that ε_1 nonlinearly increases with the increase of relative deviatoric stress level D^*, and the relationship can be expressed as follows:

$$\varepsilon_1 = aD^{*m} \tag{5}$$

where a and m are test parameters, which can be determined by undrained cyclic triaxial tests.

Equation (5) is put into Eq. (1) to obtain the undrained cumulative deformation model of soft clay:

$$\varepsilon_p = aD^{*m}N^b \tag{6}$$

For soft clay in Shanghai, referring to the the test standard ASTM D5311, undrained cyclic triaxial tests were conducted under different confining pressure, initial static deviatoric stress, and dynamic stress. Fitting the test results, a=0.34, b=2.68, and m=0.39.

Undrained cumulative pore pressure model of soft clay under cyclic loads

Based on undrained cyclic tests, Huang et al. (2006) put forward a cumulative model:

$$\frac{u}{p_c} = \alpha N^\beta \tag{7}$$

where u is cumulative pore pressure; p_c is the confining pressure which is equal to the initial isotropic consolidation pressure; α is normalized pore pressure after a cyclic load; β is a constant. The relationship between α and D^* can be expressed by the exponential function as follows (Huang et al. 2006):

$$\alpha = \varsigma D^{*n} \tag{8}$$

where ς and n are constants, which can be obtained by fitting tests data from the cyclic triaxial tests.

Equation (8) is put into Eq. (7) to get normalized cumulative pore pressure model:

$$\frac{u}{p_c} = \varsigma D^{*n}N^\beta \tag{9}$$

For Shanghai soft clay, fitting the results of undrained cyclic triaxial tests, ς=0.023, n=2.19, and β=0.66.

Calculation steps of traffic-load-induced cumulative settlement of subsoil

In this study, the cumulative settlement of soft clay subsoil under traffic load was calculated by the following steps:

1. Calculating ε_p and u

   According to Eq. (3), q_{ult} can be obtained after calculating the average confining pressure p_c induced by self-weight stress of subsoil. The static stress component in subsoil after construction of the embankment is determined by numerical method; then, q_s can be calculated by the following equation:

$$q_s = \sqrt{3J_{2s}} \tag{10}$$

where J_{2s} is second invariant of the static stress deviator tensor.

The peak of dynamic stress component induced by traffic load in soft subsoil can be obtained by the dynamic numerical method, then q_d is calculated by the following equation:

$$q_d = \sqrt{3J_{2d}} \tag{11}$$

where J_{2d} is the second invariant of dynamic stress deviator tensor corresponding to the peak of dynamic stress.

D^* can be obtained by inputting q_{ult}, q_s, and q_d into Eq. (4). And then, ε_p and u are calculated by Eqs. (6) and (9), respectively.

2. Calculating cumulative settlement

   The cumulative settlement of subsoil consists of two parts: one is the undrained cumulative settlement S_1 induced by cyclic loads, and the other is the consolidation settlement S_2 induced by the dissipation of cumulative pore pressure. According to the layerwise summation method, the settlements S_1 and S_2 of a point on the subsoil surface can be calculated by the following equations, respectively:

$$S_1 = \sum_{i=1}^{n} \varepsilon_{pi} h_i \tag{12}$$

$$S_2 = \sum_{i=1}^{n} m_{vi} h_i u_i \tag{13}$$

   where ε_{pi} is the undrained cumulative plastic strain of the ith element underneath the point; h_i is the thickness of the ith element; u_i is the undrained cyclic cumulative pore pressure of the ith element; m_{vi} is the coefficient of volume compressibility of the ith element; n is the total number of calculating elements underneath the point.

Traffic-load-induced cumulative settlement calculation

In cumulative settlement calculation, the simulation of traffic loads is critical. Referring to the Chinese Specifications for the Design of Highway Asphalt Pavement (JTG D50-2004), the real traffic spectrum in the test site was converted into the standard vehicle load of 200 kN. And referring to the Chinese specification of General Code for Design of Highway Bridges and Culverts (JTG D60-2004), the standard vehicle load of 200 kN (the load class of truck-20) was applied in the middle of the carriageway. In the calculation, the vehicle load was simplified as four-point loads on the pavement shown in Fig. 3. The forces on the front and rear axles were 70 and 130 kN, respectively. The loading history of wheel load can be expressed as follows:

$$\begin{cases} F = F_{\max}\sin^2\left(\dfrac{\pi}{T_s}t\right) & 0 \le t \le T_s \\ F = 0 & t > T_s \end{cases} \tag{14}$$

where t is time; F_{max} is the wheel load peak, 65 kN for the A and B wheels, 35 kN for the C and D wheels, as shown in Fig. 3, without regard to pavement unevenness; T_s is the duration time of single vehicle load and has an inverse relationship with the vehicle speed. Herein, T_s is taken as 0.05 s, representing the equivalent vehicle speed of 80 km/h (Huang 1993).

Additional stresses in subsoil caused by self-weight of the embankment and dynamic stresses induced by vehicle load were calculated with finite difference procedure Flac^{3D} (three-dimensional fast Lagrangian analysis of continua). The mechanics parameters of the subgrade materials and soils are shown in Table 1.

In the dynamic calculation, the damping matrix was determined by the Rayleigh linear combination method:

$$\boldsymbol{C} = \eta\boldsymbol{M} + \vartheta\boldsymbol{K} \tag{15}$$

where C is damping matrix; M is mass matrix; K is stiffness matrix; η and are constants related to the intrinsic frequency and damping ratio of structure, respectively, and can be calculated by the following equations:

$$\eta = \xi\omega; \vartheta = \xi/\omega \tag{16}$$

where ω and ξ are primary circular frequency and corresponding damping ratio, respectively. By modal analysis, the primary circular frequency of the subgrade is about 12 Hz; the damping ratio is taken as 0.01.

In dynamic calculation, the method of viscous boundary proposed by Lysmer and Kuhlemeyer (1969) was employed. The normal and tangential stresses at boundaries can be expressed, respectively, as follows:

$$\sigma = \rho C_p \nu_n \tag{17}$$

$$\tau = \rho C_s \nu_s \tag{18}$$

where ρ is material density; C_p and C_s are P-wave velocity and S-wave velocity, respectively; ν_n and ν_s are normal and tangential velocity of boundary nodes, respectively.

The response histories of stress components can be obtained by dynamic calculation, and Fig. 4 shows the response curves of vertical dynamic stress underneath the midpoint of AB axle in Fig. 3. The dynamic deviatoric stress peak can be obtained by the dynamic stress component peaks. Figure 5 shows the variation curve of dynamic deviatoric stress peak with depth underneath the midpoint of AB axle. It can be seen that the dynamic deviatoric stress reduces quickly in the range of 10 m deep below ground.

After obtaining the stresses, according to the steps described in the previous section, the cumulative settlement was calculated. The undrained cumulative settlement S_1, consolidation cumulative settlement S_2, and total cumulative settlement S of subsoil induced by traffic loads under the centerline of carriageway are plotted in Fig. 6. It can be seen that traffic-load-induced settlement is mainly caused by undrained cumulative deformation. With the time after opening to traffic, the settlements increase sharply at the initial stage, then gradually grows slowly. Figure 7 shows the transverse distribution of the total settlement. It can be found that the largest settlement occurs on the carriageway. Due to the influence of subgrade slope, the transverse distribution curves of

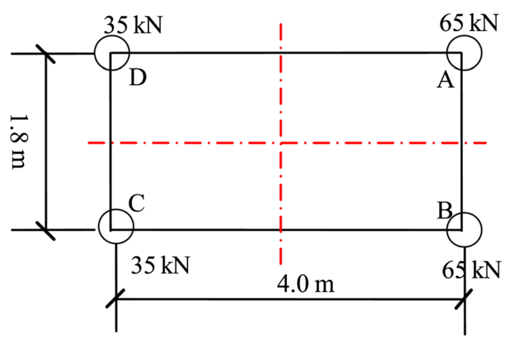

Fig. 3 Vehicle load diagram

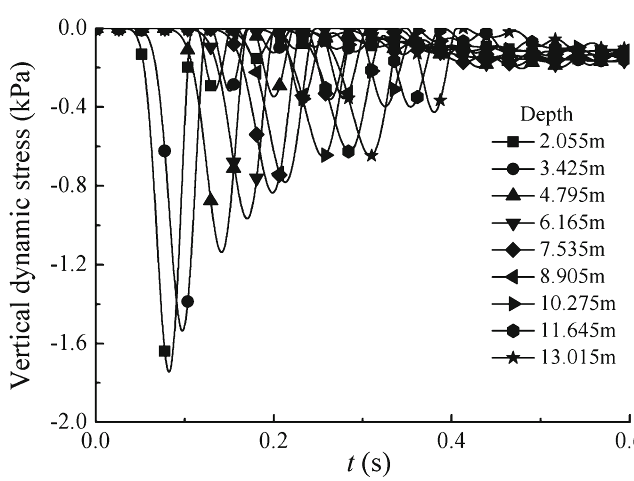

Fig. 4 Time history curves of vertical dynamic stress

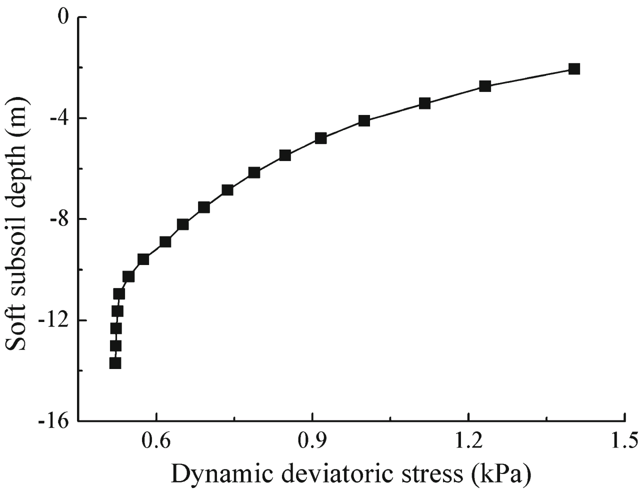

Fig. 5 Development of dynamic deviatoric stress peak with depth

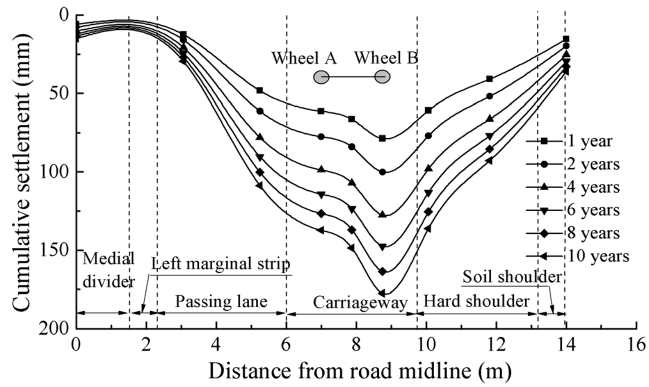

Fig. 7 Transverse distribution of soft subsoil settlement

settlement are not symmetrically about the carriageway centerline, and the settlement is comparatively larger on the side of the slope.

Comparison of calculated and field measured results

The measured cumulative settlement in the field contained the traffic-load-induced cumulative settlement and embankment-load-induced consolidation settlement. So in the calculation, the consolidation settlement due to the embankment load was considered. In this study, the embankment-load-induced settlement was calculated with the fluid-solid coupling module of the program Flac^{3D}. The mechanics parameters of embankment and soft subsoil are shown in Table 1. The calculated results are shown in Fig. 8. Compared with the traffic-load-induced cumulative settlement, the embankment-load-induced consolidation settlement is much smaller because the embankment is very low. The total settlement is mainly contributed to the traffic-load-induced cumulative settlement.

The calculated total settlement was compared with the measured results, as shown in Fig. 8. In the first 6 months, the calculated cumulative settlement is larger than the measured values, but after the 6 months, it becomes slightly smaller than the measured values. In general, the calculated settlement agrees well with the measured results. After opening to traffic for 2 years, the calculated and measured cumulative settlements are 86 and 96 mm, respectively, and there is a slight difference of 10 % between them. This indicates that the calculation method employed in this study can give a comparatively accurate prediction of the cumulative settlement of Shanghai soft clay.

Discussion and analyses

Effect of embankment height on cumulative settlement

In order to study the effect of the embankment height on the cumulative settlement, the corresponding cumulative settlements of the soft clay subsoil in Shanghai were calculated

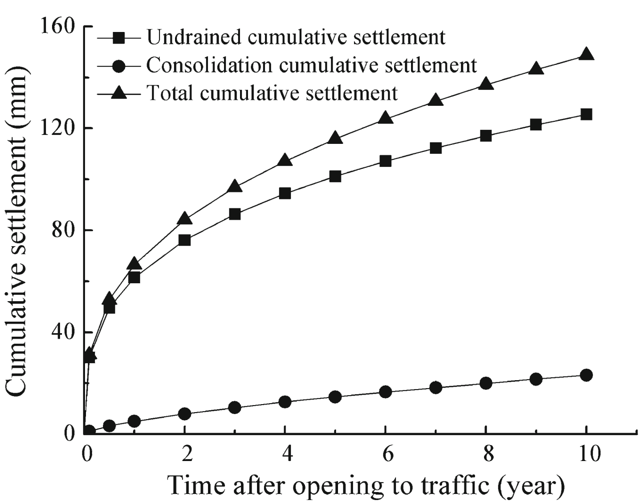

Fig. 6 Development of settlement with time after opening to traffic

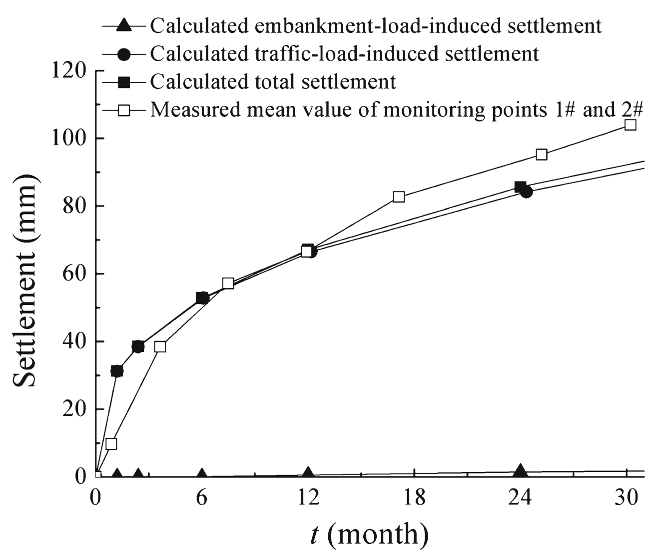

Fig. 8 Development of the settlement with time after opening to traffic

with different embankment heights (0.5, 1.0, 1.5, and 2.0 m, not including the pavement structure thickness of 0.85 m) under repeated vehicle loads of 200 kN. The average daily vehicle load number is 1,500. Figure 9 shows the variation curves of cumulative settlements of soft clay subsoil underneath the center of AB axle (as shown in Fig. 3) with time for different embankment heights. Figure 10 shows the variation curves of cumulative settlements of subsoil with the embankment height after opening to traffic for 1, 2, and 10 years.

The settlement S is divided by cumulative settlement S_{h1} corresponding to the embankment height of 1.0 m, to obtain normalized cumulative settlement S/S_{h1}. At the same time, the embankment height h is divided by 1 m to get a new dimensionless index of the embankment height ratio R_h. Figure 11 shows the variation curve of the normalized cumulative settlement S/S_{h1} with the embankment height ratio R_h. It can be seen that the relationship between S/S_{h1} and R_h is unrelated to the time of opening to traffic. It can be fitted with the following Gaussian function:

$$\frac{S}{S_{h1}} = S_0 + \frac{A}{w_h\sqrt{\pi/2}} e^{-2\frac{(R_h - R_{hc})^2}{w_h{}^2}} \tag{19}$$

where the fitting parameters S_0=0.618, R_{hc}=0.126, w_h= 1.417, A=1.281.

It can be found that when the embankment is smaller than 1.5 m, the cumulative settlement of subsoil linearly increases with the decrease of the embankment height. However, when the embankment height is larger than 1.5 m, the cumulative settlement grows slowly. Therefore, when the embankment height is less than 1.5 m, in the road design, it is necessary to consider the effect of cumulative settlement of soft subsoil.

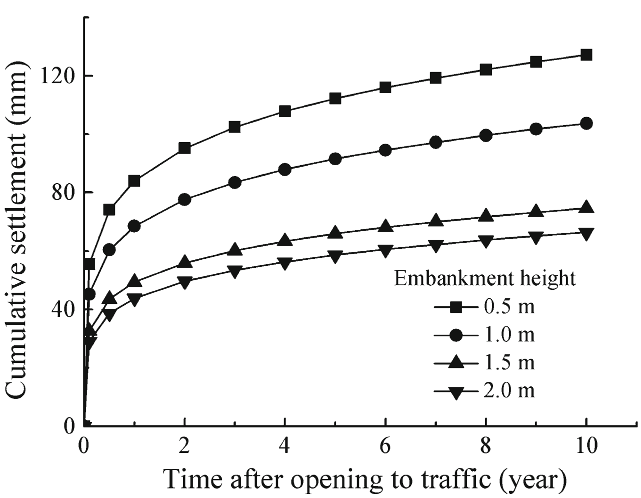

Fig. 9 Development of cumulative settlement with time for different embankment heights

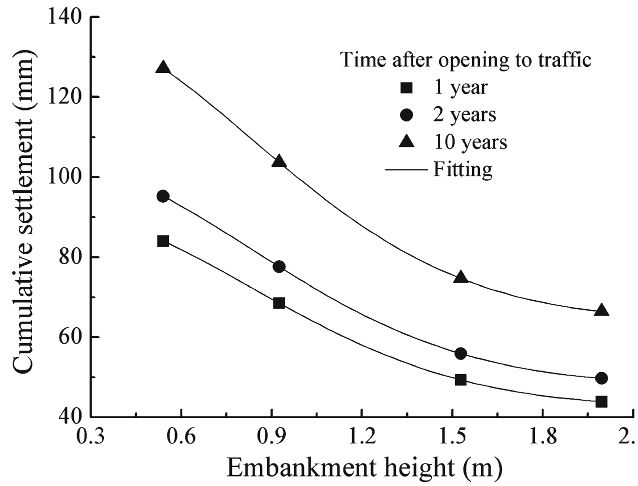

Fig. 10 Development of cumulative settlement with embankment height

Effect of vehicle loads on cumulative settlement

In order to study the effect of vehicle loads on cumulative settlement of subsoil, the cumulative settlements were calculated by taking different multiples of the vehicle load of 200 kN (0.2, 0.5, 0.8, 1.0, and 1.2 times). In the calculation, the embankment height is 1.0 m, and the average daily vehicle load number is 1,500. Figure 12 shows the variation curves of the cumulative settlement of soft clay subsoil underneath the center of AB axle with time under different vehicle loads. Figure 13 shows the variation curves of cumulative settlements with the vehicle loads after opening to traffic for 1, 2, and 10 years.

The settlement S is divided by the cumulative settlement S_{F200} corresponding to the vehicle load of 200 kN to obtain the normalized cumulative settlement S/S_{F200}. The vehicle load is divided by the standard vehicle load of 200 kN to get the vehicle load ratio R_F. The relation curves of the normalization

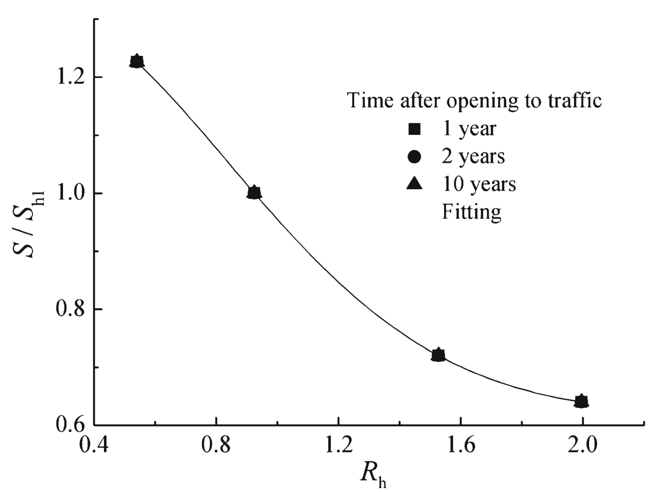

Fig. 11 Development of normalized cumulative settlement with embankment height ratio

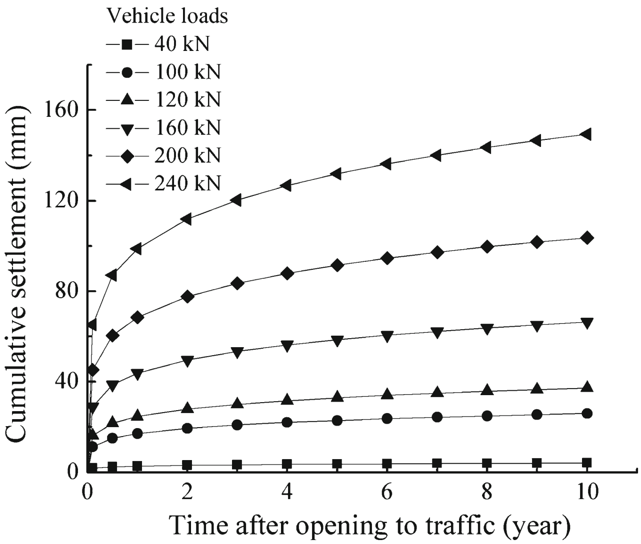

Fig. 12 Development of cumulative settlement with time for different vehicle loads

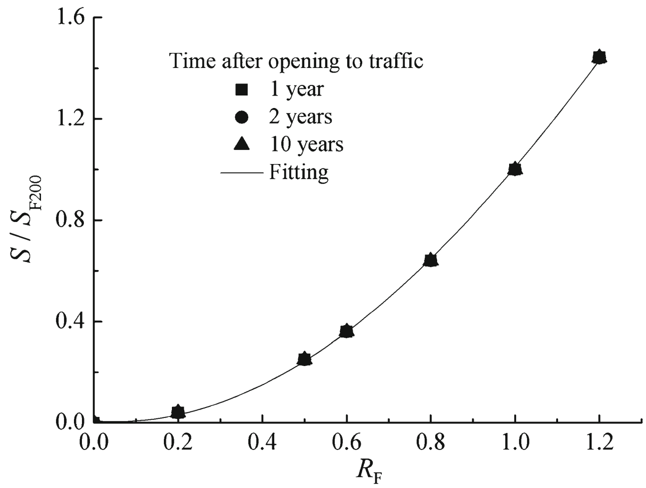

Fig. 14 Development of normalization cumulative settlement with vehicle load ratio

cumulative settlement S/S_{F200} and the vehicle load ratio R_F is shown in Fig. 14. It can be seen that the relationship between S/S_{F200} and R_F is irrelevant for the time of opening to traffic. It can be fitted with the following Gaussian function:

$$\frac{S}{S_{F200}} = S_0 + \frac{A}{w_F\sqrt{\pi/2}} e^{-2\frac{(R_F - R_{Fc})^2}{w_F^2}} \tag{20}$$

where the fitting parameters S_0=7.811, R_{Fc}=0.047, w_F= 3.629, A=−35.509.

It can be found from Fig. 14 that with the increase of vehicle loads, the cumulative settlement grows quickly. When the vehicle loads increase from 0 to 40 kN, the increase of cumulative settlement is 0.033 times that induced by the vehicle load of 200 kN. But when the vehicle load increases from 200 to 240 kN, the increased cumulative settlement is 0.44 times. This illustrates that overloading of vehicles can cause serious cumulative settlement of subsoil, thus leading to damages of embankment and pavement structure. Therefore, limiting overloaded vehicles is crucial to reducing cumulative settlement and prolonging the service life of the road. The above analyses also confirm that the cumulative settlement induced by the vehicle load less than 40 kN can be ignored in road design.

Relationship of cumulative settlement with embankment height and vehicle loads

For different embankment heights and vehicle loads, the cumulative settlements S of the subsoil (Figs. 9 and 12) are divided by the 10-year cumulative settlement S_{10} to obtain normalized cumulative settlement S/S_{10}. The time

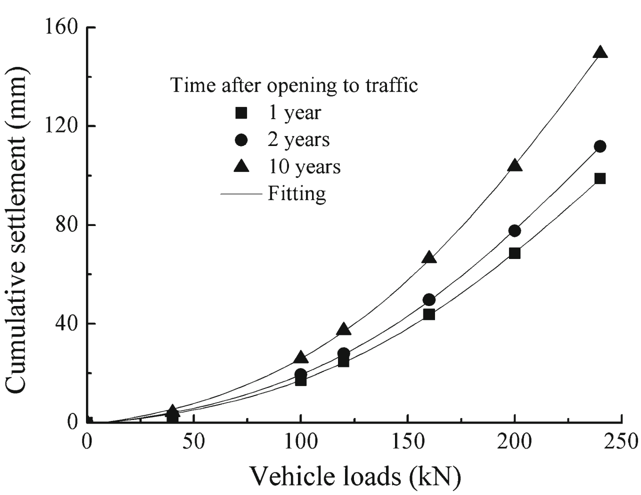

Fig. 13 Development of cumulative settlement with vehicle loads

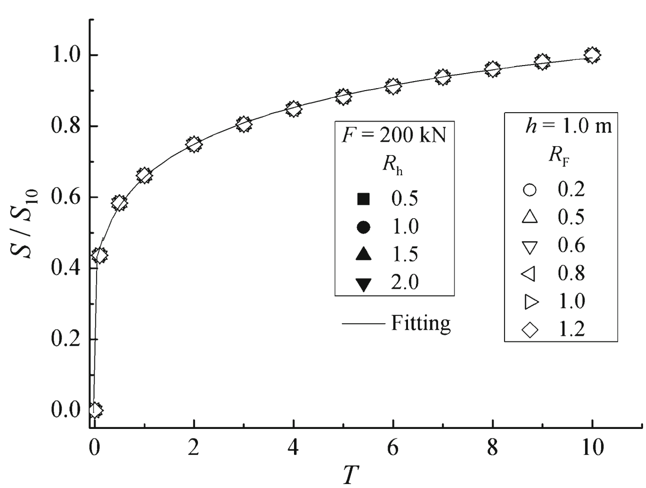

Fig. 15 Development of normalized cumulative settlement with normalized time

t is divided by 1 year to get normalized time T. The variation curves of S/S_{10} with T in different cases are shown in Fig. 15. It can be seen that the relationship between S/S_{10} and T is unrelated to the embankment heights and vehicle loads. All the cases can be fitted with the following equation:

$$\left.\begin{aligned} \frac{S}{S_{10}} &= 10\left[a_1-(a_1-a_2)e^{-(0.1c)^k}\right]T \quad T\leq 0.1 \\ \frac{S}{S_{10}} &= a_1-(a_1-a_2)e^{-(cT)^k} \quad T>0.1 \end{aligned}\right\} \tag{21}$$

where the fitting parameters a_1=1.245, a_2=0.278, c=0.190, k=0.430.

It can be found from Fig. 15 that in one-tenth of a year after opening to traffic, S/S_{10} linearly increases with time. At the early stage after opening to traffic, S/S_{10} grows quickly, and then its increase rate becomes more and more slowly. The early settlement makes up a large proportion of the total cumulative settlement. For the daily vehicle load numbers of 1,500, the cumulative settlement after 0.1 years is over 0.4 times that after 10 years; the 1-year cumulative settlement accounts for two thirds of the 10-year cumulative settlement.

It can be seen from Eqs. (19) and (20) that for the same subsoil and pavement structure, the relationship of the 10-year settlement S_{10} with the normalized embankment height R_h and normalized vehicle load R_F can be expressed with Gaussian function. If considering both the influences of R_h and R_F, S_{10} can be fitted with the following equation:

$$S_{10} = P_0 + P_1 e^{-2\frac{(R_h-R_{hc})^2}{w_h^2}} + P_2 e^{-2\frac{(R_F-R_{Fc})^2}{w_F^2}} \tag{22}$$

where the fitting parameters P_0=−12.313, P_1=48.691, and P_2=228.154.

In order to demonstrate the fitting effect of Eq. (22), the calculated cumulative settlements corresponding to four embankment heights and six vehicle loads and the fitting values with Eq. (22) are described in Fig. 16. It can be found that all points basically lie on a line with the slope equal to 1. This indicates that Eq. (22) has a good fitting effect.

Considering the influence of the embankment heights and vehicle loads, Eqs. (21) and (22) provide a prediction model of the cumulative settlement of Shanghai soft clay subsoil. In this study, the daily vehicle load number was taken as 1,500, and for the other cases, the time in the model can be directly modified according to the linear relation between the vehicle load numbers and time. For example, when the daily vehicle load numbers is 3,000, T in Eq. (21) should be substituted by $2T$. After knowing traffic volume, axle load spectrum, and embankment height, it is feasible to predict the cumulative settlement with the model.

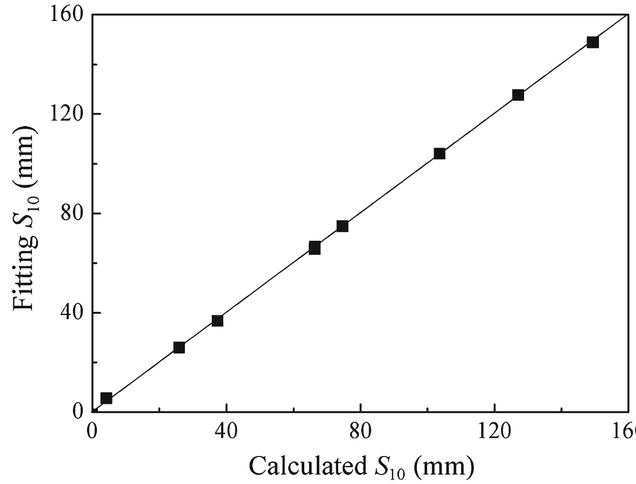

Fig. 16 Fitting effect diagram

Conclusions

By in situ tests and numerical calculations, the traffic-load-induced cumulative settlement of Shanghai soft clay subsoil under low embankment were studied. The main conclusions are drawn as follows:

1. The calculated cumulative settlements agree well with tested. The calculation method employed in this study can give a comparatively accurate prediction of the cumulative settlement of Shanghai soft clay.
2. Compared with the settlement induced by the dissipation of cumulative pore pressure, the undrained settlement induced by traffic loads is the main part of the total cumulative settlement.
3. The relation of the cumulative settlement with the embankment height and vehicle load can be expressed with a Gaussian function. When the embankment height is less than 1.5 m, it is significant in the road design to take the effect of the cumulative settlement of soft subsoil into account. The overloading of vehicle can cause significant cumulative settlement, so limiting overloaded vehicles is crucial to reducing cumulative settlement.
4. The presented prediction model of cumulative settlement of soft clay subsoil reflects well the effects of the embankment height and vehicle loads.

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