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In situ tests simulating traffic-load-induced settlement of alluvial silt subsoil

Xinzhuang Cui *, Na Zhang, Jiong Zhang, Zhijun Gao

The Department of Transportation Engineering, School of Civil Engineering, Shandong University, No. 17922, Jingshi Road, Jinan, Shandong Province, PR China

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A B S T R A C T

In China, The Yellow River delta is the youngest large river delta, and the low liquid limit alluvial silt is widely distributed there. The silt is easy to liquefy so that the silt subsoil shows large settlement under traffic load. At present, few in situ model tests were conducted to study the traffic-load-induced settlement of silt subsoil. Therefore, a falling-weight simulation equipment of traffic load was developed. By adjusting the technical parameters such as the falling height of the weight, different types of traffic loads can be well simulated. With the equipment, in situ tests were carried out to study cumulative settlement of silt subsoil in the Yellow River delta. Tests indicate that the settlement and excess pore water pressures rapidly grow initially and then tend to be stable with increasing the number of load cycles, and they also increase with the magnitude of the traffic load. When the load attains a threshold value, liquefaction takes place in the silt subsoil. After terminating loading, the pore water pressure rapidly decreases and the settlement increases simultaneously, while after one hour they tend to stabilize. Based on Chai–Miura cumulative deformation model of soil, the traffic-load-induced cumulative settlement of silt subsoil was calculated and compared with the test results. The calculated cumulative settlement with increasing number of load cycles agrees well with the test results, except the initial phase of cyclic loading where the settlement observed in the situ tests is overestimated. This is mainly because Chai–Miura model assumes undrained conditions while the subsoil under traffic loads is partly drained.

1. Introduction

The Yellow River is China's mother river and the Yellow River delta is a relatively young and large river delta due to frequent river diversion in history. The Yellow River flows through the Loess Plateau and delivers sediment into the Bohai Sea. The sediments deposit at the river mouth and form the Yellow River delta. Alluvial silt is widely distributed in the Yellow River delta and it is newly formed underconsolidated deposit. It has unique characteristics of low liquid limit and plasticity index, small cohesion, low strength, intensive capillarity and poor graduation and water stability, and it is liquefiable soil.

In the near future, a quantity of expressways will be built in the Yellow River delta due to the economic development. In order to occupy less cultivated land and reduce excessive settlement of the underconsolidated subsoil caused by the weight of subgrade, it is necessary to adopt the design method of low road embankment in the Yellow River delta. Note that in this paper, the pavement means the composite structure of surface course, base and subbase, the embankment means the compacted soil layer below the subbase of a road, and the subsoil means the natural soil below a road embankment. The term subgrade includes all layers above natural ground surface. For a road with low embankment constructed on weak subsoil, the traffic-load-induced permanent deformation of the subsoil is one of the important factors which control the design life as well as the maintenance costs of the road. Fujikawa and Miura [1] found that the traffic-load-induced settlement is about 400–600 mm for a low embankment, which is a relatively large settlement in comparison to the allowable settlement for highways. The traffic-load-induced settlement of Chinese Shenzhen–Shantou expressway was found to be about 300 mm though the subsoil was treated with the surcharge preloading method [2]. Large cumulative settlement of subsoil speeds up the destruction of pavement, and leads to great change of transverse slope of pavement and serious ponding on the road. It brings about not only road diseases such as water damage but also traffic safety problems.

Some researchers employed numerical methods like finite element calculations to analyze settlement induced by cyclic load. The development of numerical methods aimed at predicting the behavior of geotechnical structures subject to repeated loading requires the formulation of constitutive models for the constituent soils which are suitable for cyclic loading. Such models may be

* Corresponding author. Tel.: +86 13011744518.
E-mail addresses: cuixz@sdu.edu.cn (X. Cui), znazna@163.com (N. Zhang), jiongzhang@sdu.edu.cn (J. Zhang), 529370405@qq.com (Z. Gao).

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"implicit" or "explicit". The conventional implicit models are expressed within the framework of elasto-plasticity or hypoplasticity. Explicit (N-type) models directly predict the accumulation of residual strain with increasing number of cycles. For example, relied upon an explicit formulation, a general structure analysis approach was developed by Abdelkrim et al. [3] to predict the traffic-load-induced residual settlement. Niemunis and his co-workers [4] presented a high-cycle explicit model for the accumulation of strain in sand due to small cyclic loading and gave attention to the theoretical aspects of the constitutive description of the cumulative settlement. A large experimental investigation of strain accumulation in granular soils due to long-term cyclic loading is done by Wichtmann [5]. However, using implicit models for the numerical calculations, the number of cycles is usually restricted to a low number. This is due to the large calculation effort on one hand and due to the accumulation of the numerical error on the other hand. The numerical error can become excessive because the number of calculated strain increments is usually large in implicit calculations. Therefore, such implicit models are not suitable for traffic loading. While using explicit models, the number of calculated increments (Delta N) is much lower in numerical calculations, i.e., the numerical error is much less. Furthermore, such models are not restricted with respect to the number of cycles. But the application of sophisticated explicit models may not be justified in the case of simple boundary value problems like a pavement under traffic loading.

A number of empirical models has been proposed to predict the permanent deformation under repeated load. Among them, the power model proposed by Monismith et al. [6] has been widely used. Li and Selig [7] modified the Monismith model based on a large number of laboratory tests, and the dynamic deviatoric stress and static strength of the soil were introduced into the model. Furthermore, Li and Selig [8] showed some successful applications of the modified model to predict the settlement of cohesive soils under train loading. However, the Li–Selig model ignored the effect of the initial static deviatoric stress on the cumulative deformation. Considering the initial static deviatoric stress, Chai and Miura [9] modified the Li–Selig model and applied this model to calculate the permanent settlement of road with a low embankment on soft subsoil. By the multilayer elastic theory, the traffic-load-induced dynamic stress in the subsoil was calculated. Meanwhile, the embankment-load-induced consolidation settlement was simulated by finite element method, and the traffic-load-induced settlement was calculated by the Chai–Miura model. The sum of both types of settlement was compared with the measured data which included deformations of pavement, subbase, subgrade and soft subsoil. The calculated results agreed well with the measured data, although the calculated results were larger at the initial phase and smaller afterwards.

In experimental studies, in the early 1950s, Seed and his co-workers [10,11] studied the settlement behavior of roads under repeated loads by oedometric compression tests. Monismith et al. [6] analyzed the characteristics of permanent deformation of subsoil due to repeated loadings based on cyclic triaxial compression tests. Fujiwara and coworkers [12,13] researched the effect of preloading on the cumulative settlement of clay under cyclic loadings. They concluded that the amount of settlement that occurs after construction depends strongly on the soil overconsolidation ratio, degree of consolidation at the time of unloading, static loading magnitude, and repeated loading magnitude. Yıldırım and Erşan [14] tested cyclic and post-cyclic consolidation settlements of soft clay caused by cyclic loading through undrained cyclic simple shear tests in the laboratory. Shahu et al. [15] studied cumulative plastic strain of a quasi-saturated compacted silty clay under cyclic load by cyclic undrained triaxial tests. Cyclic triaxial tests were also conducted by Liu and Xiao [16] to study the behavior of silt subsoil under various physical states and stress conditions. Though these small-scale specimen tests can evaluate the traffic-load-induced cumulative deformation of subsoil, the results cannot be easily transferred to pavement because the stress and boundary conditions are more complex in real practice.

In order to reflect practical conditions of subsoil in the field, some large-scale physical model tests were carried out. A large-scale bench test was conducted by Bodin-Bourgoin [17] to determine the lateral displacement of ballast. Indraratna [18] carried out a large-scale triaxial test on clay subjected to cyclic loading representing a typical track environment to predict the behavior of soft estuarine subsoil. Huo [19] conducted large-scale model tests to predict the permanent settlement of a composite foundation under cyclic loading. In general, large-scale physical model tests provide reliable results that can reflect the global behavior of cumulative settlement. However, with the limit of the physical model size and inaccurate settings of boundary conditions, the large-scale model tests also cannot perfectly simulate the cumulative settlement occuring in practice.

Therefore, it is necessary to conduct in situ tests for a quantification of the traffic-load-induced settlement of subsoil. In this paper, a simulation equipment of traffic load is described. The design parameters of the equipment are studied to reflect the characteristics of traffic load. With the developed equipment, in situ tests are performed to study traffic-load-induced cumulative settlement of silt subsoil in the Yellow River delta. The in situ test results are compared with numerical calculation results using the model of Chai and Miura.

2. In situ tests

2.1. Description of the site

The test site is located in working section of Xinhe-Xinzhuangzi expressway, as shown in Fig. 1. The subsoil in this area is the low liquid limit silt and geomechanical parameters are shown in Table 1. Groundwater is 0.6 m below the ground surface. Due to intensive capillarity, the average saturation of silt above the groundwater is as much as 0.78. The mean grain size of the subsoil is 0.03 mm. The coefficient of curvature of soil gradation curve is $C_c = d_{30}^2/(d_{60}d_{10}) = 1.08$, and the coefficient of uniformity is $C_u = d_{60}/d_{10} = 3.25$, so the gradation of the soil is poor. A X-ray diffractometer test indicates that non-clay mineral content in the soil is more than 80%.

Electron probe JXA-8800R was employed to analyze the microstructures of silt particles. Fig. 2 shows that the microstructures of test site silt and normal silt particles are obviously different. The normal silt for comparison was piedmont alluvial soil in Jinan with clay removed. Compared with normal silt, the Yellow River delta silt particles were fully rounded with few elongated and flaky particles, and the surface of the particle was crushed and denuded by long time soaking erosion and scouring.

2.2. In situ simulation equipment of traffic load

A falling-weight traffic load simulation equipment (FWTLSE) was developed to measure the cumulative settlement of subsoil. The FWTLSE is mainly composed of three parts: loading system, pneumatic system and automatic control system (Fig. 3). Loading system is made up of loading plate, air spring and supports. The air spring is an inflatable rubber device which takes the place of a steel spring. The stiffness of air spring is changed to simulate the effect of different heights of embankment on the attenuation of wheel-load-induced stress wave. The pneumatic system is