Transportation Geotechnics 14 (2018) 8–21

Contents lists available at ScienceDirect

Transportation Geotechnics

journal homepage: www.elsevier.com/locate/trgeo

Finite element analysis on the dynamic behavior of soil arching effect in piled embankment

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ARTICLE INFO

Article history:
Received 22 September 2016
Revised 20 August 2017
Accepted 1 September 2017

Keywords:
Soil arching
Dynamic loads
Piled embankment
Finite element analysis

ABSTRACT

Most research conducted so far has investigated the soil arching in piled embankment under static loads, knowledge on their dynamic behaviors under transient loads of moving vehicles is rather limited in the literature, especially considering the subsoil consolidation, and therefore it deserves more research attention. This paper presented a series of finite element (FE) models to investigate the dynamic behavior of soil arching effect in piled embankment. At a given load cycle number of 300, since the subsoil was not fully consolidated, 'Model B' yielded much smaller results in terms of both the settlement and earth pressure coefficient than 'Model A', with the difference of approximately 50%. A three-dimensional (3D) column model with a simplified subsoil consolidation procedure (Model E) was presented to simplify the problem of time-consuming and difficult to convergence. A close agreement was observed between the two models both in terms of the settlement and the earth pressure coefficient of the embankment, and therefore concluded that 'Model E' was much more suitable for the simulation of piled embankment under dynamic loads. The parametric study relating to the dynamic load type, velocity and vehicle wheel load showed that the soil arching effect remained valid, but was reduced under dynamic loads, especially when the vehicle wheel load and velocity were relatively large. The dynamic load type was found to have an obvious influence on the soil arching effect, in which the settlement increased by approximately 6% when varying the half-sine load type to the sine load type. As expected, the increased vehicle wheel load and velocity aggravated the dynamic vertical stress and settlement of the piled embankment.

Introduction

Soil arching is a common phenomenon in piled embankments resting on subsoils, and has long been recognized in the theory of soil mechanics [22]. Consequently, several design methods are proposed for the assessment of soil arching in piled embankment based on various concepts [13,21,20,5,8,24]. Since the complex of the soil arching in piled embankments, numerical simulation has been the main mechanistic approach due to its ability to incorporate advanced material characterization models to predict more accurately the behavior, such as deformations, stresses, and strains in the piled embankments. Fully three-dimensional (3D) analyses have been performed to investigate the stress concentrations developed at the edge of the pile, the tensile forces and strains developed in the geosynthetic layer [1,16,3]. However, the fully 3D numerical modeling usually can be very complicated, needs computers with a high processing power, and also can be extremely time consuming depending on the complexity of the problem [2]. Therefore, for practical limitation, the piled embankments have been simulated using unit cell concept and 3D column models [15,27,26,3,30,31].

Most research conducted so far has investigated the behavior of soil arching in piled embankment under static loads, knowledge on their dynamic behaviors under transient loads of moving vehicles is rather limited in the literature. After the piled embankments are put into use, the soil arching existing in piled embankments will inevitably be subjected to cyclic dynamic traffic loads, which will result in a reduction of soil arching. Specifically, the behavior of dynamic stress transfer in this embankment system under dynamic loads is not well known, especially considering the consolidation of the soft foundation, and therefore it deserves more research attention.

The consolidation of subsoil is a process in which the soil settles as a consequence of the application of external loading. Initially, the external loading is transferred to the pore water in the subsoil, resulting in the generation of excess pore pressure and pressure

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https://doi.org/10.1016/j.trgeo.2017.09.001

gradient. As time passing by, the pore water permeates driven by the pressure gradient through the void between soil particles, promoting the pore pressure to dissipate gradually. In this process, the external loading is gradually transferred from the pore water to the soil particles, which mainly depends on the permeability of the soil [4]. Immediately after external loadings are applied to a saturated soil domain, all the external pressure transfers to water, certain amount of time are required for the dissipation of this excess pore water pressure to the solid phase. When this dissipation is complete (i.e. total drainage has taken place), the solid phase totally takes the external pressure, which is converted to effective stress. Most of the previous investigations mainly paid their attention to the dynamic response of piled embankments, and neglected the procedure of subsoil consolidation, which assumed that all the initial values, including the displacements, velocity and stresses are all zero [12,11,23,9,10,28,17]. Obviously, the assumption made by previous investigations is not consistent with the real situations. Actually, the stresses and strain in piled embankments absolutely are not zero at the stage of construction due to the subsoil consolidation. This assumption would make the evaluation of load transfer and deformation of the piled embankments under dynamic loads lowly reliable [25].

Generally, when a piled embankment is put into use, the generation of water pressure due to the application of dynamic loads and the dissipation of water pressure due to the subsoil consolidation would take place at the same time, which will make the problem further more complicated. In this case, the coupling effects between solid and fluid phases need to be considered comprehensively to achieve an accurate solution [33,18]. Since the relatively low permeability of the subsoil, the consolidation period may be relatively long, and the required cyclic number of the dynamic loads to be applied in the numerical model would be significantly large. This will result in the problem of time-consuming and difficult to convergence, which is not in general applicable for the analysis of the piled embankment under dynamic loads.

Since the main purpose of this paper is to investigate the dynamic behavior of soil arching effect in piled embankments rather than the generation and dissipation of the pore water pressure, a 3D column model with a simplified subsoil consolidation procedure is presented. Firstly, the appropriateness of the 3D column model is validated by comparing with the results of the full 3D model and the measurements of a test embankment by Chen et al. [6]. Then, the finite element (FE) models with different simulation sequences of the soil consolidation and dynamic loads are comprehensively compared. Finally, the influence of dynamic load type, velocity and vehicle wheel load on the soil arching effect under dynamic loads are investigated, whose results are presented as a discussion in terms of the settlement, vertical stress and earth pressure coefficient.

FE modeling

General description

A hypothetical reinforced piled embankment constructed on subsoil is shown in Fig. 1. A 40 m wide embankment with the height of 5.9 m and side slopes of 1V:1H is constructed on a uniform 10 m thick soft clay layer below which a rigid layer exists. A total thickness of 0.6 m pavement including the 0.15 m AC layer, 0.20 m base layer and 0.25 m subbase layer is placed at the top of the embankment. The ground water table is located at the top of the clay layer. The concrete square shaped pile, with the square pile cap of 1 m width and 0.5 m thickness, are assumed to be installed in a square grid pattern with the spacing of 2.5 m, and the width of the pile is 0.3 m. A layer of geogrid with the stiffness J = 3 MN/m is also considered, at a small height 0.1 m above the base of the embankment.

Due to symmetry, only one-quarter of the pile and its tributary area is modeled, as shown in Fig. 2. Thus, a 'unit cell' with square dimensions of half the center-to-center pile spacing (s/2) is used herein, which are carried out using the FE package 'ABAQUS' (version 6.12). With regard to the displacement boundary condition, no displacements in the direction perpendicular to the symmetry planes and to the base are allowed. For the hydraulic boundary condition, the phreatic level is set at the top surface of the clay layer to generate a hydrostatic pore-water pressure profile in the domain. A zero pore pressure (u_w = 0 kPa) boundary condition is applied at the top and bottom boundaries to model free drainage, which means that the water is allowed to drain via the top and bottom surface of the soft clay. In the FE models, 8-node stress-pore pressure coupled brick elements (C3D8P) are used to represent the soft clay, while 8-node brick elements (C3D8) are used for the embankment fill and the pile. The biaxial geogrid is represented using 4-node, full integration, 3-dimensional membrane elements (M3D4), with non-zero stiffness only in the orthogonal directions along the square 'grid' of pile caps, as described in Zhuang and Ellis [32].

Constitutive models

With regard to the constitutive modeling, the soft subsoil is modeled as the Modified Cam Clay (MCC) material. A linear-elastic, perfectly plastic model with the Mohr–Coulomb failure criterion is used to model the embankment fill. The pile, pavement material and geogrid are modeled as linear elastic material. The parameters used in the analysis are summarized in Table 1. The interface friction angle between the geogrid and the embankment is assumed to be equal to the friction angle of the embankment fill, as assumed in Liu et al. [16]. According to the equation proposed by Potyondy [19] for the clay, the interface friction angle (φ_i) between pile and the subsoil can be determined as follows:

$$\varphi_i = (0.6 \sim 0.8)\varphi' \tag{1}$$

where φ' is the friction angle of the soil. In this analysis, the ratio of the interface friction angle (φ_i) and the friction angle of the soil (φ') is assumed as 0.7.

In addition, the initial yield surface size a_0, a required input for the MCC model, is computed using the following:

$$a_0 = \frac{1}{2}\exp\left[(1+e_0)\frac{e_N - e_0\kappa \ln p_0}{\lambda - \kappa}\right] \tag{2}$$

where e_0 is the initial void ratio; p_0 is the overburden pressure; e_N is the intercept of the normally consolidated line with ratio axis in $e - \ln p'$ plane; λ is the slope of the virgin consolidation line and κ is the slope of the swelling line. The trend of increasing a_0 with depth is taken into consideration by dividing the clay layer into 20 equal thickness vertical sections and assigning the computed a_0 value at mid-depth for each vertical section.

Simulation procedure

After establishing the initial stress and pore pressure conditions together with the boundary condition described earlier, the embankment construction is simulated in five stages. The embankment and pavement loading is simulated by adding layers of elements simulating the fill in all models. Each embankment fill placement is assumed to be completed in 15 days, and followed by a 10-day consolidation period. During this period, the subsoil is allowed to drain. A consolidation period of 630 days, followed by the embankment construction, is carried out until the excess