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Effects of asphalt overlay on XCC pile-supported embankment vibration from a moving vehicle

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ABSTRACT

Vibration behaviors of the asphalt pavement-embankment-X-shaped cast-in-situ concrete (XCC) piles reinforced ground system under a moving vehicle are simulated through three-dimensional finite element approach. The influences of asphalt overlays on displacement pattern on the top of pavement, the asymmetric movement of surrounding soil around XCC piles, and the concentration coefficient after laying the overlay are investigated. The obtained results show that the dynamic displacement decreases as a consequence of the increasing stiffness of this system after laying asphalt overlays. It is also shown that the vertical displacement of soil around piles decreases as the thickness of overlays increases. Meanwhile, the asymmetric extent, in which there is an obvious differential displacement between the flat and concave area, is presented. In addition, the concentration coefficient for the embankment's top flat is significantly larger than that for the slope surface, and its increasing is caused by asphalt overlays.

1. Introduction

Asphalt overlay has been increasingly used to eliminate the differential settlement as a rapid construction technique for highway embankments over soft soil. A variety of studies about asphalt overlay have been conducted, which always focus on the characteristics of road materials and the design of the pavement, such as the formation [1], propagation [2] and prevention [3] of cracks. However, they have paid very limited attention to the geomechanical behavior of the asphalt overlay (e.g., the vibration properties, the loading transfer mechanism).

In recent years, a lot of research on dynamic analysis of pavements and soft ground under moving vehicles has been conducted. The linear elastic material model [4] and four inelastic material models [5] for flexible pavements were considered in 3D FEM models for the analysis of dynamic response of road pavements under moving loads. A nonlinear model based on the shear modulus reduction curve was adopted by Shih et al. [6] to study the influence of the soil nonlinearity on the critical speed and stress-strain behavior of the embankment and ground. However, a fully 3D simulation (millions of finite elements) using nonlinear soil model is difficult due to the computational efficiency. Correia dos Santos [7] presented an efficient procedure based on a FEM/BEM coupling formulated in time domain to investigate the vibration problems of a fully 3D model induced by railway traffic. The equivalent linear model [8], which involves an iterative procedure that can approximate nonlinear behavior of soil, was usually used in order to save computational resources in fully FEM simulations. Meanwhile, a new method, cast-in-place concrete piles with an X-shaped cross-section (XCC piles), has been developed and used widely in expressway and railway engineering [9] to solve the differential settlement problems. While the objectives of most previous studies [10,11] are so far only to investigate the static behavior of a single XCC pile, or XCC pile groups, the knowledge on the entire pavement-embankment-XCC piles reinforced ground system under moving vehicles is rather limited in the literature. Specifically, the effect of asphalt overlays on the vibration generated by a moving vehicle, and the asymmetric characteristics relating to XCC piles are not well known.

In this study, a three-dimensional finite-element model of the pavement-embankment-XCC piles reinforced ground system was developed and validated by an available analytical solution. Based on the above model, a case study was conducted to investigate the dynamic characteristics of this system with asphalt overlays. Study attention is focused on the effect of asphalt overlays on the displacement pattern at the top of this embankment system, and the asymmetric behavior of surrounding soil around XCC piles. Through the concentration coefficient, the influence of asphalt overlays on this system was investigated.

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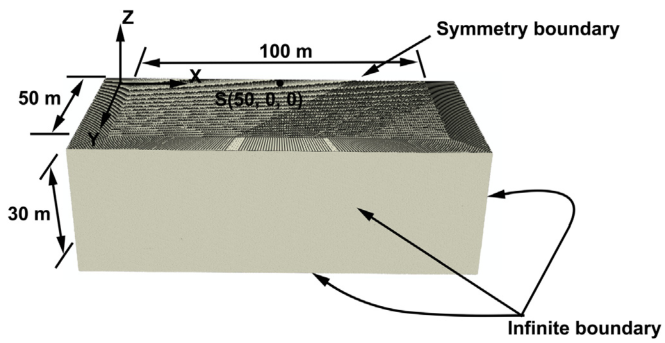

Fig. 1. Finite element model.

2. Simulation approach and validation

To validate the accuracy by the simulation approach, a concentrated force at the speed of 210 km/h on an elastic half-space is considered. The results obtained by the finite element analyses are compared with the analytical solution by Frýba [12], who derived the solutions of a moving force in elastic half-space at the motion speed lesser than the velocity of propagation of transverse waves. The length, width and depth of the finite element are 100 m, 50 m and 30 m, respectively. Only a half of model was built considering the symmetry as shown in Fig. 1. The symmetry boundary was restrained from the moving in Y-direction, and the Lysmer-Kuhlemeyer (LK) infinite elements, which can minimize the influence of wave reflection on observation locations of interest, were used on the remaining boundaries to represent the infinite boundary condition. Three mesh densities with element size of 0.21 m, 0.38 m and 0.62 m were considered to indicate that the adopted mesh density was large enough to propagate the vibration from the source to the concern point. In Fig. 1, point S located at (50, 0, 0) was chosen to be the concern. The interior domain of the model was meshed using 8-node cubic hexahedral elements with reduced integration and hourglass control.

The amplitude spectra at location S is presented in Fig. 2. It shows that only the result with the element size of 0.21 m gets close to Frýba's solution. Meanwhile, it represents well the velocity amplitude at all important frequencies of the vehicles, 0–20 Hz. Therefore, this case of 0.21 m element size and the simulation approach can give accurate results of the velocity.

3. Model description

The case of expressway widening projects with cast-in-situ X-shaped cross-section concrete piles (XCC piles) in the Fourth Yangtze River Bridge in Nanjing was selected. The pile spacing s and length l are 3 m and 17.6 m, respectively. The three parameters of XCC pile cross-section – the outsourcing diameter R_{out}, the open arc angle α and the open arc distance L - are 0.611 m, 130°, and 0.12 m, respectively. The XCC pile-supported embankment system comprises a stone mastic asphalt (SMA) pavement of 0.18 m which is underlain by cement stabilized crushed stone base (CTB) of 0.4 m overlaying a 3 m-thick embankment. There is a silty clay layer of 3.2 m which underlies the upper expressway system. Underneath the upper silty clay layer were a clay layer of 9.5 m, a silt layer of 4.9 m and a lower silty clay layer of 17.4 m in sequence from the ground to the bedrock. The rigid bedrock is assumed below the lower silty clay layer. A full description of the model geometry is shown in Fig. 3. The selected car moves along the axis of the model from the speed of 60 km/h to 180 km/h, and the standard contact pressure is 0.7 MPa. The tire-ground contact shape is assumed to be a rectangle with the width of 0.22 m and the length of 0.25 m. The geometry and load parameters of the vehicle are shown in Fig. 4.

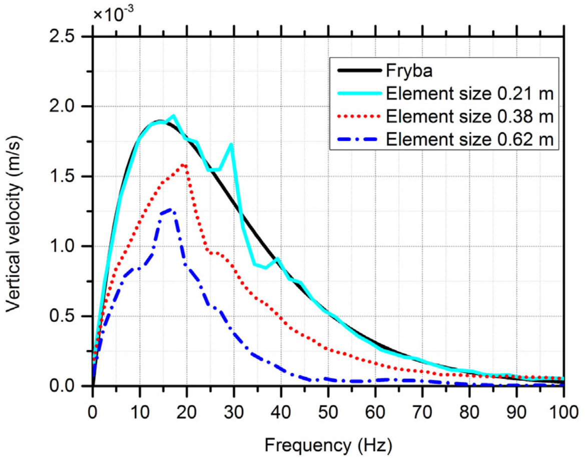

Fig. 2. The amplitude spectra at location P:.

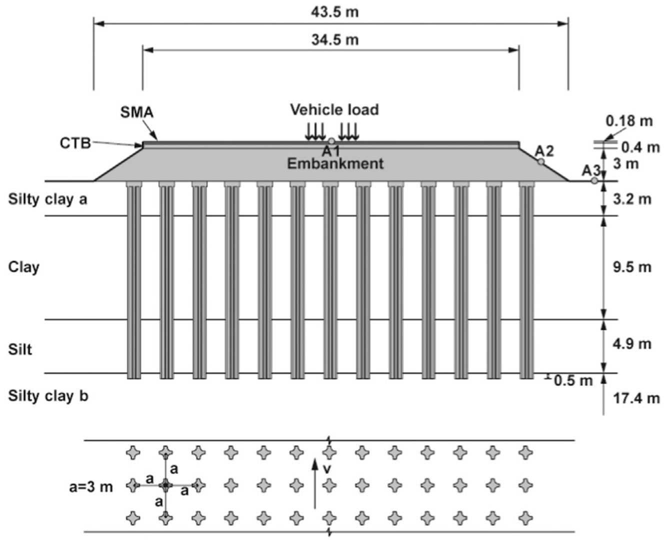

Fig. 3. Geometry of XCC pile-supported embankment.

As shown in Fig. 5, a full scale finite-element model of the expressway reinforced by XCC piles was built. Its total length and width are 100 m and 73.5 m, respectively. The model was meshed using 8-node linear hexahedral elements with reduced integration and hourglass control. In this paper, LK infinite elements were used to represent the infinite boundary condition and minimize the influence of wave reflection. The model was surrounded by LK elements, and the fixed boundary was used at the bottom. The nonlinear behavior of soil was simulated approximatively in present study by means of the equivalent linear approach. The modulus degradation and damping curves in Fig. 6 were used in the simulation. The equivalent linear material parameters used in this study are listed in Table 1, which were calculated through a number of linear iterations. The time step used in this simulation is 5×10^{-5} s, which is small enough to satisfy the solution accuracy.

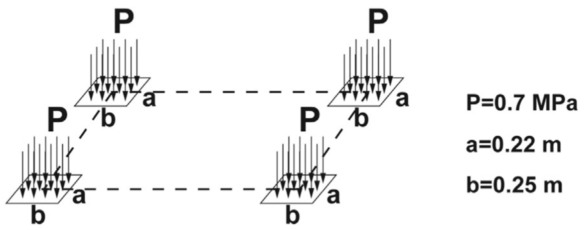

Fig. 4. Geometry and loads of the vehicle.