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Displacements of column-supported embankments over soft clay after widening considering soil consolidation and column layout: Numerical analysis

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Abstract

The common challenges for constructing embankments on soft clay include low bearing capacity, large total and differential settlements, and slope instability. Different techniques have been adopted to improve soft clay, such as the use of foundation columns including stone columns, deep mixed columns, and vibro-concrete columns, etc. Due to increased traffic volume, column-supported embankments may be widened to accommodate the traffic capacity need. Adding a new embankment to an existing embankment generates additional stresses and deformations under not only the widened portion but also the existing embankment. Differential settlements between and within the existing embankment and the widened portion may cause pavement distresses. Limited research has been conducted so far to investigate widening of column-supported embankments. In this study, a two-dimensional finite difference numerical method was adopted. This numerical method was first verified against field data and then used for the analysis of widened column-supported embankments over soft clay. The modified Cam-Clay model was used to model the soil under the existing embankment and the widened portion. Mechanically and hydraulically coupled numerical models were created to consider the consolidation of the foundation soil under the existing embankment and the widened portion. Different layouts of foundation columns under the existing embankment and the widened portion were investigated. The numerical results presented in this paper include the vertical and horizontal displacements, the maximum settlements, the transverse gradient changes, and the stress concentration ratios, which depended on column spacing. The columns installed under the connection side slope were most effective in reducing the total and differential settlements, horizontal displacement, and transverse gradient change of the widened embankment.

Keywords: Column; Consolidation; Embankment; Numerical method; Settlement; Soft clay; Widening

1. Introduction

Widening of embankments has been increasingly adopted in practice to increase highway capacities due to demand for higher traffic volume than previously designed. The 1989 Government's White Paper “Roads for Prosperity” (The Highway Agency, 1991) indicated that “about 60% of the motorway network in England as well as some truck roads will need to be widened by the provision of additional lanes”.

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The process of adding a new embankment adjacent to the existing embankment generates additional stresses and deformations underneath both the existing embankment and the widened portion. Ling et al. (2003) confirmed that a number of roadway pavements were exposed to overstresses due to widening of existing roads in China (Han et al., 2006). Ling et al. (2003) proposed some design criteria for widening of embankments.

The common challenges for constructing embankments on soft clay including embankment widening are low bearing capacity, large total and differential settlements, and slope instability. Different technologies have been used in practice to avoid, minimize or remedy roadway distresses due to the widening of embankments, such as the use of lightweight backfill, geosynthetic reinforcement, over-excavation and replacement, installation of piles or foundation columns, preloading, and a combination of the above alternatives. Foundation columns may include sand columns, stone columns, deep mixed (DM) columns, vibro-concrete columns, etc. DM columns were selected in this study as an example. Column-supported embankments have been increasingly used in soft soils in the past few years. A large numbers of studies have been conducted on this topic, for example, Han and Gabr (2002), Collin et al. (2005), Huang et al. (2005), (2009), Chen et al. (2008), Zheng et al. (2011), Filz et al. (2012), Khabbazian et al. (2012). Several factors influence the performance of column-supported embankments. The effect of the column stiffness on the displacement behavior is an obvious one, which has been investigated by the second author and his co-authors (Han and Gabr, 2002; Huang et al., 2009; Huang and Han, 2010).

Even though widening of embankments has been increasingly adopted in practice, so far very limited guidance for design is available for widening projects, especially for widening of column-supported embankments. Forsman and Uotinen (1999) investigated the effect of geosynthetic reinforcement on the settlements and horizontal displacements of embankments after widening. Geosynthetic reinforcement may not be needed if the spacing of columns is close and/or the height of the embankment is large. Han et al. (2007) investigated stresses and deformations of the widened embankments over soft soil with or without foundation columns. In this study, Han et al. (2007) modeled the soft soil as a linearly elastic–perfectly plastic material with the criterion of Mohr–Coulomb failure. This model cannot consider property change of the soft soil due to the reduction in the soil volume during the consolidation process. To overcome this problem, Han et al. (2007) assumed the improved properties of the soil after the consolidation. Mirjalili et al. (2012) presented a two-dimensional numerical analysis of a constructed levee on a DM column-improved foundation by widening the back slope of the normal river embankment to a broad width over soft clays improved by sand compaction columns and sand drains. In this numerical analysis, the finite element method was adopted to simulate the clay layers using an elasto-viscoplastic constitutive model proposed by Kimoto and Oka (2005). This constitutive model was an extension to the Cam-Clay model to overcome the structural degradation of the soil skeleton by considering the shrinkage of both the overconsolidated boundary surface and the static yield surface with respect to the accumulation of viscoplastic strain.

The modified Cam-Clay model was employed in this study to represent the behavior of the soft clay under the existing embankment and the widened portion (i.e., the influence of volume change due to consolidation on soil properties is taken into consideration). The modified Cam-Clay model is an incremental hardening/softening elastoplastic model. Its features include a particular form of nonlinear elasticity and a hardening/softening behavior governed by volumetric plastic strain. The failure envelopes as investigated by Wood (1990) and Roscoe and Burland (1968) correspond to ellipsoids of rotation about the mean stress axis in the principal stress space. The Modified Cam Clay was classified as an incremental hardening/softening elastoplastic model based on the FLAC manual (Itasca, 2002a). Based on Roscoe and Burland (1968), the Modified Cam Clay (MCC) can be defined that the yield surface of the MCC is described by an ellipse and therefore the plastic strain increment vector (which is perpendicular to the yield surface) for the largest value of the mean effective stress is horizontal, and hence no incremental deviatoric plastic strain takes place for a change in mean effective stress (for purely hydrostatic states of stress). This is very convenient for constitutive modeling in numerical analysis. Based on Schofield and Worth (1968), Hardening phenomenon can be described as follows. Due to the positive volumetric strain-increment, soil in a stressed state will compact to a smaller total volume at which it has a new larger yield curve. The soil becomes denser and a permanent load-increment can be added before bringing it to the verge of yielding as a point on the larger yield curve. At this stage, the soil is slightly deformed to be stronger or harder. In contrast, due to negative volumetric strain for a soil in another stressed state, the sample must expand to a larger volume and in this condition the new 'looser' soil is just in equilibrium governed by a smaller yield curve. The effect leads to the specimen being weaker or softer: this process is called softening. Therefore, the MCC model can consider strain hardening and softening. However, strain softening happens for highly over-consolidated soils when the applied stress is higher than the initial yield stress. The plastic flow rule is associated and no resistance to tensile mean stress is allowed.

The objective of this paper was to investigate the effect of column layouts under existing and widened embankments on the displacement behavior using mechanically and hydraulically coupled numerical models considering consolidation. Particular attention was paid to the settlements, horizontal displacements, transverse gradients, and vertical stresses. The 2D numerical method was first verified against the measured field data available in the literature. Different layouts of columns under the existing embankment and the widened portion were investigated to evaluate their effectiveness.

2. Verification of numerical model

To ensure the reasonableness of the numerical model to be used for the parametric study, a field case study as described