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Research Paper

Arching in geogrid-reinforced pile-supported embankments over silty clay of medium compressibility: Field data and analytical solution

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ABSTRACT

The objective of this study is to improve the understanding of load transfer mechanism of Geogrid-Reinforced Pile-Supported Embankments (GRPS) via a new 3D analytical approach and comprehensive field tests. A full-scale embankment was built over a silty clay of medium compressibility as a part of the Liuzhou-to-Nanning High-speed Railway (LNHR) in China. Six sections of the embankment have been heavily instrumented producing comprehensive data of high quality. Field measurements evidence the existence of soil arching, membrane contribution and ground reaction, phenomena that are all contributing to load transfer mechanism. The new 3D analytical arching model accounts for a triangular arrangement of piles and, unlike existing methods, accounts for all relevant components of load transfer mechanisms. In addition, two key parameters were introduced in the model: an elastoplastic state parameter of soil arching (α) and a coefficient of equivalent uniform stress (β). The former was used to satisfy the load equilibrium in case of partial arching while the latter was adopted to allow possible nonuniform vertical stress acting on the ground surface. The so-called ground reaction method was incorporated in an innovative manner to take into account the reactive support of the subsoil beneath geogrid-reinforced layer when estimating the tension development in the geogrid. Finally, the performance of the proposed model was assessed against several existing models and field measurements. Results showed that the new model presented herein outperforms existing models and satisfactorily predicts both the pile efficiency and tension development within the geogrid.

1. Introduction

Designing and constructing road and railway embankments over problematic soils, such as soft soils, expansive soils or liquefiable soils, is not trivial because of the excessive total and differential settlements, low bearing capacity, large lateral displacement and slope instability resulting from such soils (e.g. [1–3]). To mitigate these issues, engineers resort to a variety of ground improvement methods such as preloading, stage construction and pile foundations (e.g. [4–6]). Recently, Geogrid-Reinforced and Pile-Supported (GRPS) embankments have gained much popularity due to its inherent short construction time and the efficiency in reducing both vertical and horizontal displacements (see reviews by [7,8]). A GRPS embankment is a complex soil-structure interaction system (see Fig. 1) that efficiently combines vertical piles (floating or end-bearing) with caps and geogrid-reinforced earth platform. GRPS embankments have been adopted as a technical solution for most high-speed railways in China (e.g. [9,10]). Although it is acknowledged that embankment loads are transmitted to the piles by a soil arching effect in the embankment fill and via the geogrid layer [11], the exact process of development of load transfer between embankment mattress and piles is still not well understood. With its comprehensive dataset, this paper will bring new information on this aspect.

When it comes to soil arching, most models were developed for square piles configuration, at the exception of the work by Kempfert et al. [12] who considered a triangular layout for relatively low embankments but effectively produced a 2D design. A large number of models are analytical and based on different simplifying assumptions about load transfer mechanisms (see reviews by [8,11,13–15]). Van Eekelen et al. [16] proposed to organize these

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Nomenclature

H	embankment height
L	pile length
s	pile cap spacing
d_p	pile diameter
d_c	pile cap diameter
d_s	width of square pile cap
s_s	pile cap spacing for square arrangement
L_{soil}	thickness of soil layer
l_g	elongated lengthof geogridbetween caps
η	normalized net cap spacing
r	radial distance
A_S	tributary area of soil between piles
A_p	area of pile cap
σ_s	ground pressure measured on subsoil
σ_p	ground pressure measured on pile caps
P_p	total force on pile caps
T	uniform tensile force of geogrid
T_f	tensile force from field test
χ and λ	fitting parameters of k-$H/(s-d_c)$ curves
α_1, α_2	angle of load diffusion
Re	radius of spatial arching
A	total composite area allocated to each pile
A_e	an unit area of three adjacent pile caps
σ_r	radial stress
σ_θ	hoop stress
$\bar{\sigma}_{sa}$ and $\bar{\sigma}_{sb}$	equivalent uniform stress acting ongeogrid
τ_{top} and τ_{bottom}	shear stress acting on geogrid
γ	unit weight of embankment fill
K_p	Rankine earth pressure coefficient
α	elastoplastic state parameter
β	coefficient of equivalent uniform soil pressure
OCR	over-consolidation ratio
E_p	pile efficiency
m	replacement ratio
ϕ	internal friction angle of fill material
K_g	tensile stiffness of geogrid
k	ground reaction moduli
ε_g	axial strain of geogrid
δ_{as}	average pile cap settlement
δ_s	ground settlement measured between two adjacent piles
T_a	tensile force provided by analytical model
H_f	final embankment height
C_c	arching coefficient
σ_{below}, σ_{within}, σ_{above}	radial stress below, within and above spatial arching, respectively
p	characteristic value of live load
l_o	initial length of geogrid

models in three main categories: (i) limit-state equilibrium models (e.g. [12,16–19]), (ii) frictional models (e.g. [20,21]), and (iii) rigid arch models (e.g. [22]). It has been showed that these approaches give considerably different results in terms of load distribution between piles and surrounding soils [13,23]. In addition, the load transfer mechanisms within GRPS embankment have also been studied via numerical methods, for instance, using finite element method (FEM) (e.g. [24,25]), finite difference method (FDM) (e.g. [3,26]) and discrete element method (DEM) (e.g. [11,27,28]).

Regarding the loading mechanism of geogrids (Fig. 1), several 2D analytical methods have been developed [29–32], and some were extended to three-dimensional cases (e.g. [12,20]). Most of these methods were developed for embankments over soft soils where the upwards ground counter-pressure (illustrated in Fig. 1) on the geogrid is negligible. However, in case of the subsoil of medium compressibility, ignoring this counter-pressure may result in significant overestimation of the required geogrid tensile strength.

Validation of design models requires extensive and good quality data and researchers often employ reduced scale models to validate empirical and numerical approaches [15,20,33–38] while only a limited number of full scale tests have been carried out [9,10,14,39–43]. Full-scale field tests are extremely time-consuming and expensive to conduct and, hence, full-scale data on GRPS are very rare in the literature. Nonetheless, full-scale tests are critical to improve our understanding of GRPS embankments and to validate the existing design methods.

Considering the popularity of equilateral triangular piles configuration in the Chinese high-speed railway network and the extent of the railway network, there is a need for a rigorous 3D triangular design approach coupled to experimental validation in case of high embankments. So far, such model is not available in the literature. In addition, neglecting the soil counter pressure on the geogrid, as it is often done in existing methods, leads to an overdesign of the geogrid, and consequently, an unnecessary over-cost. The present

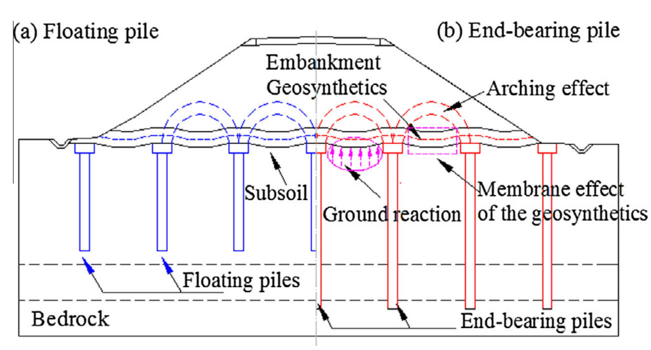

Fig. 1. Sketch of an embankment reinforced by geogrids and floating piles (a) or end-bearing piles (b).

research will constitute a step towards establishing an innovative and more cost-effective approach. To do so, this paper presents the derivation and validation of a new 3D model for triangular arrangement of piles with a geogrid. The innovation also lies within the fact that, unlike existing methods, the new model accounts for all relevant load transfer mechanisms. These are the progressive development of soil arching, the non-uniform distribution of stress on the ground, a non negligible ground reaction and the progressive development of tension in the geogrid. The penultimate section of the paper will demonstrate how the new model yields much better predictions than existing methods. The validation was made possible by the extensive and high quality data coming from a test embankment of the Liuzhou-to-Nanning High-speed Railway (LNHR, China) where six sections where instrumented [9]. The extensive and rare data presented in this paper will contribute to a better understanding of the load transfer mechanisms in GRPS.