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Technical note

Analytical study for double-layer geosynthetic reinforced load transfer platform on column improved soft soil

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The objective of this study is to propose a reasonably accurate mechanical model for double-layer geosynthetic reinforced load transfer platform (LTP) on column reinforced soft soil which can be used by practicing engineers. The developed model is very useful to study the behaviour of LTP resting on soft soil improved with conventional columns such as concrete columns, piles, and deep soil mixing columns. The negligible tensile strength of granular material in LTP, bending and shear deformations of LTP, compressibility and shearing of soft soil have been incorporated in the model. Furthermore, the results from the proposed model simulating the soft soil as Kerr foundation model are compared to the corresponding solutions when the soft soil is idealised by Winkler and Pasternak foundation models. It is observed from the comparison that the presented model can be used as a tool for a better prediction of the LTP behaviour with multi layers of geosynthetics, in comparison with the situation that soft soil is modelled by Winkler and Pasternak foundations. Furthermore, parametric studies show that as the column spacing increases, the maximum deflection of LTP and normalised tension in the geosynthetics also increase. Whereas, the maximum deflection of LTP and normalised tension in the geosynthetics decrease with increasing LTP thickness, stiffness of subsoil, and stiffness of geosynthetic reinforcement. In addition, it is observed that the use of one stronger geosynthetic layer (e.g. 1 × 2000 kN/m) with the equivalent stiffness of two geosynthetic layers (e.g. 2 × 1000 kN/m) does not result in the same settlement of LTP and the tension of the geosynthetic reinforcement when compared to two weaker geosynthetic layers.

1. Introduction

Insufficient bearing capacity and excessive settlement are very common and severe issues of soft soils when heavy superstructures are constructed on the top of these soils (Parsa-Pajouh et al., 2016). Thus, in combination with cautious field observations and laboratory tests, the use of ground improvement techniques using rigid (e.g. concrete injected columns, jet grouted columns, and piles) or semi-rigid inclusions (e.g. deep soil mixing columns and lime-cement columns) has grown substantially over the last two decades (Bergado et al., 1999; Han et al., 2004). Load transfer platform (LTP), a layer of sand or gravel consisting of geosynthetic layers, is commonly placed over the columns (e.g. concrete injected columns, or piles) used for ground improvement to facilitate the load transfer from the superstructures to the columns (Russell and Pierpoint, 1997; Han and Gabr, 2002; Kempfert et al., 2004).

Application of a load transfer platform resting on column improved soft soil is very common, particularly when highway embankments are built on improved ground. To analyse the column supported embankments, several analytical models have been proposed in the literature. Van Eekelen et al. (2013) summarised and classified them as (a) frictional models (Terzaghi, 1943; McKelvey, 1994; Russell and Pierpoint, 1997; Naughton, 2007; McGuire et al., 2012), (b) rigid arch models (Carlsson, 1987; Rogbeck et al., 1998; Svanø et al., 2000; Van Eekelen et al., 2003), (c) models using mechanical elements (Deb, 2010; Filz et al., 2012; Zhang et al., 2012a, b; Deb and Mohapatra, 2013) and (d) limit-state equilibrium models (Marston and Anderson, 1913; Hewlett and Randolph, 1988; Jones et al., 1990; Zaeske, 2001). British design

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guidelines BS8006 (2010), discussed by Van Eekelen et al. (2011), adopted the empirical model proposed by Jones et al. (1990) to study the geosynthetic reinforced column supported embankments. Zaeske's model (2001) latter was adopted in the German design guidelines EBGEO (2010). Van Eekelen et al. (2013) proposed a new limit-state equilibrium model for piled embankments which is an extension of the model proposed by Hewlett and Randolph (1988) and EBGEO (2010). Several other researchers compared the results of existing analytical models with field or laboratory measurements (Chen et al., 2008, 2010; Briançon and Simon, 2012; Girout et al., 2016). Chen et al. (2008) conducted experiments both with and without geosynthetics and compared the results of their experiments with existing analytical models, namely Terzaghi (1943) and Low et al. (1994) and the original 2D equation of Marston and Anderson (1913). Zaeske (2001), Heitz (2006), and Farag (2008) compared the results of their laboratory model tests with their predictions from the calculations. Results of a predictive model to capture membrane behaviour of the geosynthetic reinforcement based on the results of twelve model tests have been reported by Van Eekelen et al. (2012a, b). Several other studies have been conducted using two dimensional numerical models of geosynthetic reinforced column supported embankment structures adopting the finite element method (FEM) and finite difference method (FDM) (Han et al., 2007; Huang et al., 2009; Huang and Han, 2010; Yapage and Liyanapathirana, 2014). Furthermore, the predictions adopting full-width model were compared with unit cell model in numerical simulations by Bhasi and Rajagopal (2015), Khabbazian et al. (2015), and Yu and Bathurst (2017). Collin et al. (2005) proposed a mechanical model of multiple layers of low strength geogrids within the LTP based on the concept of "beam" theory. But, the interrelationship between the embankment settlement and strain in the geosynthetics was ignored in that study. However, application of a load transfer platform is not limited to the column supported embankments. Load transfer platform is widely used for heavy superstructures such as fuel tanks and silos. The practical designs of LTP demand the simple yet accurate modelling of (i) the mechanical behaviour of the LTP, (ii) the mechanical behaviour of the underneath soft soil, and (iii) the interaction mechanism between the LTP and the soft soil.

While physically close and mathematically simple idealisations of the mechanical behaviour of the geosynthetic reinforced granular fill or LTP can be established adopting Timoshenko (Yin, 2000a, b; Shukla and Yin, 2003; Zhao et al., 2016) or the Euler-Bernoulli beam theories (Maheshwari et al., 2004; Maheshwari and Viladkar, 2009; Zhang et al., 2012a, b) or even the Pasternak shear layer theory (Yin, 1997a, b; Deb et al., 2007; Deb, 2010), the characteristics that represent the mechanical behaviour of the soft soil and its interaction with the granular layer are difficult to model. Since in reality, the soft soil is heterogeneous, anisotropic and nonlinear in load-displacement response, the simple springs cannot simulate the soil response accurately. It should be noted that the most commonly used mechanical model to simulate the soil is the one developed by Winkler (1867). Although, the model proposed by Van Eekelen et al. (2013) can be applicable for both full and partial arching which results in a better representation of the arching measured in the experiments than the other existing models such as EBGEO (2010), BS8006 (2010), especially when the embankment is relatively thin, Van Eekelen et al. (2013) modelled the subsoil as an elastic spring with constant modulus of subgrade reaction which is comparable to linear Winkler's springs. Winkler's idealisation symbolises the soil medium as a series of identical but mutually independent, closely spaced, linearly elastic spring elements. Since according to the Winkler hypothesis, there is no interaction between adjacent springs, this model cannot account for the dispersion of the load with depth and distance from the loading area. However, it is a common phenomenon that the surface deflections occur not only immediately under the loaded region but also within certain limited regions beyond the loaded area. Therefore, Winkler's model has the inability to take into account the continuity or shear strength of the soil. Hence, compressibility of the soil was considered in the model proposed by Van Eekelen et al. (2013) while shear action in the soil was ignored. To overcome the weaknesses of the Winkler's model (i.e. to achieve some degree of interaction between the individual spring elements), some modified foundation models have been suggested in the literature. In these modified models, a second parameter was introduced to Winkler foundation to eliminate the discontinuous behaviour of soil by providing continuity through interaction between the individual spring elements with some structural elements (Filonenko-Borodich, 1940; Hetényi, 1946; Pasternak, 1954). To further improve the two-parameter foundation models, the third soil parameter was introduced, leading to the so-called "three-parameter" foundation model. Among several three-parameter foundation models, the foundation model proposed by Kerr (1965) is of particular interest since it geneses from the well-known Pasternak foundation model for which several applications and solutions have been already available in the literature. Kerr foundation model consists of two spring layers, with varied spring constants, interconnected by a shear layer. Furthermore, Kerr concluded that for different types of foundation materials (e.g. soil and foam), the Winkler foundation model cannot realistically predict the interaction mechanisms between the beams and the contacting soil medium. Therefore, the most important task for practicing engineers is to simulate soft soil, which demands simple modelling but provides an accurate response of the soft soil.

Mechanical behaviour of the geosynthetic reinforced granular fill or LTP can be theoretically established by adopting the Pasternak shear layer theory (Yin, 1997a, b; Deb et al., 2007; Deb, 2010), the Euler-Bernoulli beam theory (Maheshwari et al., 2004; Maheshwari and Viladkar, 2009; Zhang et al., 2012a, b), and the Timoshenko beam theory (Yin, 2000a, b; Shukla and Yin, 2003; Zhao et al., 2016). According to Pasternak theory, the cross-section of the LTP does not rotate and therefore, the granular layer experiences transverse shear deformation only. Thus, bending deformation of the granular layer was ignored in the developed models (Yin, 1997a, b; Deb et al., 2007; Deb, 2010). For application of the Euler-Bernoulli theory in geosynthetic reinforced soil (Maheshwari et al., 2004; Maheshwari and Viladkar, 2009; Zhang et al., 2012a, b), by considering the plane sections remain plane and perpendicular to the neutral axis after deformation, the shear deformation of a geosynthetic reinforced soil was ignored. However, after deformation of beams with the small length - to depth ratio, the cross section of the beam is still not be perpendicular to the neutral axis. To overcome the shortcomings of Euler-Bernoulli and Pasternak theories, the well-known Timoshenko (1921) beam can be adopted to simulate the LTP (Yin, 2000a, b). Yin (2000a, b) idealised the soft soil, the granular layer, and the geosynthetics by linear Winkler springs, Timoshenko beam, and a rough membrane, respectively. Based on the Timoshenko (1921) beam assumption, Yin's model considers the shear and the flexural deformations of the granular layer since the rotation between the cross section and the bending line of the beam is acceptable. However, the model considered a linear behaviour for soft soil, and the infinite tensile stiffness for the granular fill materials was assumed while column supports were not considered. Zhao et al. (2016) proposed a new dual beam model for a geosynthetic-reinforced granular fill with an

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