Geotextiles and Geomembranes xxx (2017) 1–15

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

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

The effect of geotextile reinforcement and prefabricated vertical drains on the stability and settlement of embankments

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ARTICLE INFO

Article history:
Received 3 December 2016
Received in revised form
9 June 2017
Accepted 2 July 2017
Available online xxx

Keywords:
Geosynthetics
Reinforcement
PVD
Smearing
Numerical modeling
Creep

ABSTRACT

The construction of four dikes on deep strata of very soft clay has required the application of several measures to improve the performance of the foundation, such as very wide berms, basal geotextile reinforcement and prefabricated vertical drains (PVDs). In order to control the rate of construction, the foundation and the dikes have been monitored with settlement plates, topographic stakes, inclinometers and piezometers. The use of back-analysis has allowed finding the adequate material model, the smearing of drains and the coefficient of secondary compression necessary to attain a good agreement between the measurements supplied by the instrumentation and the calculated values obtained with an elastic-viscoplastic (EVP) finite element (FE) program. Both the geotextile reinforcement and the PVDs produce an important increase in the safety factor (SF). The PVDs produce a significant acceleration in settlements, but the influence of the geotextile in the settlements is negligible. The combined use of the geosynthetic reinforcement and PVDs enhances embankment performance substantially more than the use of either method of soil improvement alone. The importance of flow in the results has been established.

1. Introduction

When embankments are constructed over weak soils such as soft clay, problems of short-term instability may arise and a number of solutions have been proposed to mitigate this instability. Before the advent of the methods of ground improvement, these problems were overcome by constructing the embankment with very flat side slopes or berms.

This measure may be complemented or substituted by using a basal layer of geotextile reinforcement placed over the soft soil. If correctly designed and installed, the geotextile will impart tensile strength to the base of the fill, thereby resisting lateral spreading (Ingold and Miller, 1988). Another technique that has been widely used is to install a sand blanket on the ground surface and prefabricated vertical drains (PVDs) in the soft soil connected to it. In this case, the construction of the embankment must follow a time schedule so that the gain in strength produced by drainage will be enough to avoid instability. Finally, another measure is to install both drainage and ground improvement (stone columns).

As it will be shown in the Literature review, many papers have been written on the use of PVDs to improve the safety factor (SF) or accelerate the settlements of the soil foundation and some others have presented the advantages that basal geotextiles offer to increase the safety or the possibility of reducing the settlements, but in few papers both procedures have been compared or combined. Even more, in the published cases, the lateral displacements have usually been overpredicted. This paper is aimed at filling this gap, presenting a well monitored embankment under which both PVDs and basal geotextiles have been used. The scope of this paper is to find parameters and soil models that will duly predict settlements, pore pressures and lateral displacements, by considering the smearing of PVDs, the necessity of using material models that take into account the creep of the soft foundation soil and the influence of flow in the results.

2. Literature review

Justo (1966) carried out a thorough study on the construction, theory and performance of vertical sand drains, concluding that the drains, when properly employed, fulfilled their role in inorganic soils, as evidenced by (a) a good agreement with theory, (b) a great

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http://dx.doi.org/10.1016/j.geotexmem.2017.07.001

increase in the rate of settlement (see also Arulrajah et al., 2006, 2008), and (c) a non-occurrence of slides where drains were employed. An even more comprehensive study carried out by Magnan (1983) drew similar conclusions: an effectiveness of drains in general, except in very organic soils.

Bergado et al. (2002) compared two embankments with and without basal geotextile reinforcement on soft ground and concluded that a high-strength geotextile can significantly reduce the plastic deformation in the underlying foundation soils, subsequently increasing the collapse height of the embankment up to 1.5 times that of the unreinforced case. Chai et al. (2002), in a similar study, concluded that the base reinforcement will only have a beneficial effect on the subsoil deformations when the embankment approaches failure, whereas at a working state the reinforcement had no obvious effect on the subsoil deformation.

Arulrajah et al. (2004) and Arulrajah and Bo (2008) described the use of PVDs to accelerate the consolidation of underlying soft marine clay. The study revealed that the c_h value of the clay is lowest at the sub-area with the closest vertical drains spacing. This was attributed to the larger smear effects at locations with closer drain spacing.

Several authors used a simple approach to analyze the PVD-improved subsoil, based upon an equivalent vertical hydraulic conductivity. Shen et al. (2005) compared the performance of two full-scale embankments on soft clay and found that PVDs increased the bulk vertical hydraulic conductivity of soft subsoil by about 30 times compared to the original non-treated soil. Ma and Shen, 2011 compared measured and calculated settlements and strength increase under an embankment on soft to medium clay treated with PVDs and concluded that the Modified Cam-Clay (MCC) model can predict the settlement but not the variation of shear strength during consolidation in an acceptable way. Wu et al. (2015) carried out a similar study, adding that the shear strength predicted by Ladd et al. (1972) equation agreed well with the measured value.

Lo et al. (2008) used an axisymmetric unit cell idealization around a PVD in the analysis of a wide embankment. The horizontal permeability was determined by back analysis of the central zone during the first 12 months of settlement data. Despite the fact that the one-dimensional analysis is conservative, the observed settlement beneath the central zone of the embankment after 9 years was unambiguously higher than that of the computed final settlement. This deviation began to occur 3 years after commencement of construction, when primary consolidation was essentially complete, so that may be attributed to creep.

Rowe and Taechakumthorn (2008) presented a numerical study on the combined effect of PVDs and a basal geotextile on an EVP soil. They found that PVDs substantially reduce the effect of creep-induced excess pore pressure, and hence not only allowed a faster rate of consolidation but also improved the long-term stability of the reinforced embankment. Furthermore, PVDs work together with geosynthetic reinforcement to minimize the differential settlement and lateral deformation of the foundation. The combined use of the geosynthetic reinforcement and PVDs enhances embankment performance substantially more than the use of either method of soil improvement alone. Gnanendran et al. (2006) indicated as well the preference of an EVP soil.

Karim et al. (2010, 2011) described the performance of a geogrid-reinforced embankment on soft soil improved with PVDs. This was calculated using coupled FE analysis with two EVP models. The horizontal permeability was back-estimated using oedometer test data and the first year of field settlement data to predict long-term behavior. The predicted pore water pressure showed reasonable agreement with the measured values, whereas the predicted settlement at the center of the embankment was smaller than the measured value. The monitored geogrid force was significantly lower than the value inferred from the stability calculation, which removes any concern about the long term strength degradation of geogrid reinforcement. The magnitude of the lateral displacement was overpredicted by both models during the early period, but the amount of overprediction reduced as time progressed.

Wu et al. (2011) compared settlement and pore pressures measured and predicted by simple models in a geotextile-reinforced embankment with PVDs. They found that the maximum uncertainty in the prediction was for the radial coefficient of consolidation, due to the discontinuous nature of the sand seams.

Taechakumthorn and Rowe (2012) used a modified EVP constitutive model to simulate a reinforced test embankment brought to failure, finding good agreement with the measured vertical settlements and excess pore-water pressures, while the horizontal deformations were overpredicted. They concluded that for this particular embankment, constructed on anisotropic sensitive clay at a very fast construction rate, the geogrid reinforcement used had no significant beneficial effect before or after failure, because it was not sufficiently stiff.

Parsa-Pajouh et al. (2014) emphasized that the parameters of the smear zone have key roles on the required consolidation time to achieve a certain soil strength and stiffness. Chu et al. (2006) and Deng et al. (2017) performed large-scale laboratory model tests to assess the suitability of PVDs in the consolidation of ultra-soft soil and concluded that the discharge capacity of the drain can decrease substantially after the drain has experienced large deformations, indicating an increase in smearing.

Hu et al. (2014) carried out a large-strain EVP consolidation analysis of clay layers with PVDs, taking into account the resistance of PVDs and the smear effect, The results showed that both a small-strain EVP model and a large-strain model without creep predicted larger degrees of consolidation and could not simulate the foundation settlements during and after preloading. Nevertheless, their conclusions were questioned by Mesri and Wang (2015) that supply a very simple equation to evaluate the secondary settlement. Finally Hu et al. (2015) sustained that this equation is not always valid.

Zhang et al. (2015) presented a case history on the performance of an embankment reinforced by a layer of basal geotextile on soft deposits using an MCC model in the analysis. Both field and simulation results indicated that the geotextile had a small effect on reducing the vertical displacements of subsoil and produced a marginal increase in the overall factor of safety, due to its low stiffness (200 kN/m). In general, the excess pore pressures calculated by FE analysis were higher than the measured data.

Rujikiatkamjorn and Indraratna (2015) sustained that to make a more realistic prediction the changes in soil permeability and compressibility within the smear zone caused by the mandrel should be properly captured.

Li and Spinoza (2017) found, in a reinforced embankment on PVDs in soft soil, an empirical relationship between the degree of mobilization for the soil shear strength, K_s, the settlement over the center of the embankment, s, and the lateral displacement at the toe, δ:

$$K_s = 0.71 \cdot \delta / s + 0.2 \tag{1}$$

where K_s = ratio of mobilized shear stress to available shear strength.