Analysis and Design of Piled Geogrid-Reinforced-Earth Embankment

Nasr O. Sheta[✉] and Rudolph P. Frizzi

Langan Engineering and Environmental Services, Inc., Parsippany, NJ, USA
{Nsheta, rfrizzi}@langan.com

Abstract. A pile-supported geogrid-reinforced-earth embankment was designed and constructed to serve as an access road for heavily loaded cranes and pile-installation rigs for constructing a major bridge between New York and New Jersey in the United States. The road is to also serve as an access to maintain the bridge during its service life. Subsurface investigations performed along the proposed access road alignment revealed subsurface conditions typically consisting of surficial fill underlain by a highly compressible organic clay and/or peat overlying marine sand underlain by glacial till. A limiting-settlement criterion set forth by the crane engineer together with settlement and slope-stability analyses indicated a conventional embankment could experience non-tolerable settlement and slope instability where thick organic soils were encountered. A ground-improvement program was carried out using geogrid reinforcement, a load transfer platform (LTP), and timber elements to control settlement and enhance slope stability. Where thinner organic soils were encountered, staged construction and a monitoring program were implemented to design and construct the proposed embankment.

1 Introduction

Design and construction of embankments on deep soft soils present challenges to geotechnical engineers because of potential long-term settlement and long construction time required to improve the soft soils as well as the relatively high cost associated with soft soil treatment/improvement. Pile-supported embankments provide a practical and efficient solution for embankment construction on soft soils because of shorter construction time. However, in some cases with significantly deep soft deposits, the potential for long-term settlement can be a considerable design concern, even when pile support is considered. The use of geosynthetics-reinforced LTPs above piles enhances load transfer from the embankment to piles, minimizes loads transmitted to soft soils and, hence, reduces total and differential settlements at the base of the embankment (Anjana and Rajagopal 2012). Geosynthetics-reinforced pile-supported embankment construction also results in significantly shorter construction time, compared to time needed to perform ground improvement of soft soils, limits lateral soil pressures on adjacent structures and significantly reduces, or even eliminates, embankment settlement (van Eekelen et al. 2015).

The design of a geosynthetics-reinforced pile-supported embankment includes design of embankment geometry, which is determined based on construction requirements, integrity of the embankment soil mass, which is typically evaluated

based on slope stability analysis, and load transfer from embankment to the underlying pile-soil system, which is mainly based on soil arching, and load transfer through geosynthetics (Syawal et al. 2007). Load transfer from embankment to the underlying pile-soil system was explored both analytically and experimentally by several investigators. An approach presented by Carlsson (1987) considered a 2-D model with a triangular soil wedge centered between pile rows and transmitting its weight directly to geosynthetics and the underlying soil subgrade, while the weight of the rest of embankment soil and surcharge loads on top of embankment are directly transmitted to piles. Another approach was presented by Christopher (2014) to study the load transfer mechanism of geosynthetics-reinforced pile-supported embankments considering soil settlement and strain compatibility of the LTP. Svanø et al. (2000) developed a 3-D model to calculate the load sharing between piles and geosynthetics-subgrade system. Full-scale field tests and field instrumentation of test embankments were also performed to study behavior of geo-synthetics-reinforced pile-supported embankments (Laurent et al. 2008; Yan and Xiaoyan 2015). In addition, Poulos (2007) developed design charts of piles supporting embankments on soft clay. These design charts addressed different aspects of pile design including pile ultimate capacity, settlement and the effect of pile position below embankment. Navin (2005) also utilized finite element method (FEM) to study the stability of embankments founded on soft soils improved with deep-mixing columns. Such study recommended the use of FEM rather than limit equilibrium methods (LIMs), as embankment failure mechanisms resulting from column bending and tilting can take place, which can't be predicted by LIM.

This paper presents the analysis, design, construction and monitoring of a geosynthetics-reinforced-earth pile-supported embankment serving as an access road for heavily loaded cranes and pile-installation equipment utilized to construct a major bridge between New York and New Jersey in the United States.

2 Project Description and Subsurface Conditions

The subject site, where a \$1.5B (USD) cable-stayed double-deck bridge is to be constructed to replace an existing bridge, is located between New York and New Jersey in the United States. The subject pile-supported geogrid-reinforced-earth embankment was about 1,000 m long, about 15-m-wide (at its top), and up to 4-m-high. The subject embankment was required to serve as an access road for construction equipment including heavy cranes, and also will be utilized as an access road for maintaining the new bridge during its service life. A subsurface investigation program including drilled borings was performed along the embankment alignment. The subsurface conditions typically consisted of surficial fill underlain by organic clay and peat overlying marine sand which is underlain by glacial till overlying bedrock. Figure 1 shows typical subsurface conditions encountered along the proposed embankment.

2.1 Embankment Configuration

Fill placement was typically required to construct the proposed embankment above existing grades. The height of the embankment ranged from about 1.5 m to about 4 m.
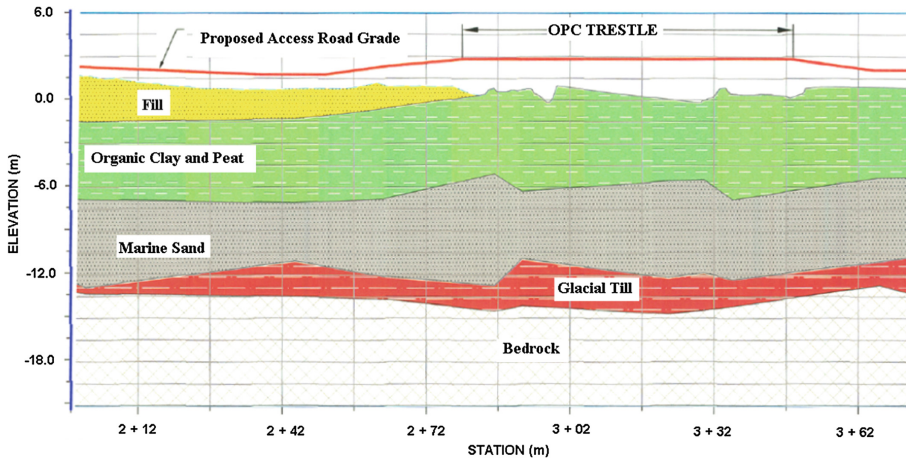
Fig. 1. Typical subsurface conditions along proposed embankment profile

Results of field and laboratory tests performed during geotechnical subsurface investigation indicated loose/soft nature of surficial fill and organic clay and peat. Loads anticipated on the proposed embankment from construction equipment including heavily loaded cranes were significantly high. A preliminary settlement analysis of a test embankment indicated proposed embankment, if supported on surficial fill and organic clay and peat soils, would experience settlements that would not be tolerable by the manufacturer of the heavily loaded cranes. Therefore, it was decided that a pile-supported structure will be necessary to reach acceptable performance of the proposed embankment. A conventional pile-supported load-relieving platform option was discussed. However, because of cost ineffectiveness considerations, this option was abandoned. Project environmental limitations precluded the use of steel, concrete, and aggregate material elements. Therefore, a geogrid-reinforced-earth embankment supported on driven timber piles was explored. The timber piles were specified as pressure-treated elements to ensure acceptable short- and long-term pile integrity. The purpose of the geogrid-reinforced-earth was to minimize piling cost by maximizing pile spacing as the geogrid-reinforced-earth mass was designed to act as a load-transfer mat to evenly distribute embankment loads on timber piles. The configuration of the proposed embankment section significantly changed along the embankment profile. The overall embankment footprint needed to be coordinated and minimized in order to limit the environmental impact on adjacent wetlands. Therefore, at some sections, a temporary vertical geogrid-reinforced-earth face had to be provided during the temporary use of the embankment, and then removed to form a permanent geogrid-reinforced earth slope, after the construction of the bridge is done (i.e. when the embankment will be used as an access road for bridge maintenance equipment). In addition, the top width of the embankment was increased at locations at which construction equipment was presumed to make turns. Figure 2 shows a typical section configuration of the proposed geogrid-reinforced-earth pile-supported embankment and Fig. 3 shows an aerial photo indicating the extent of the embankment after its construction.
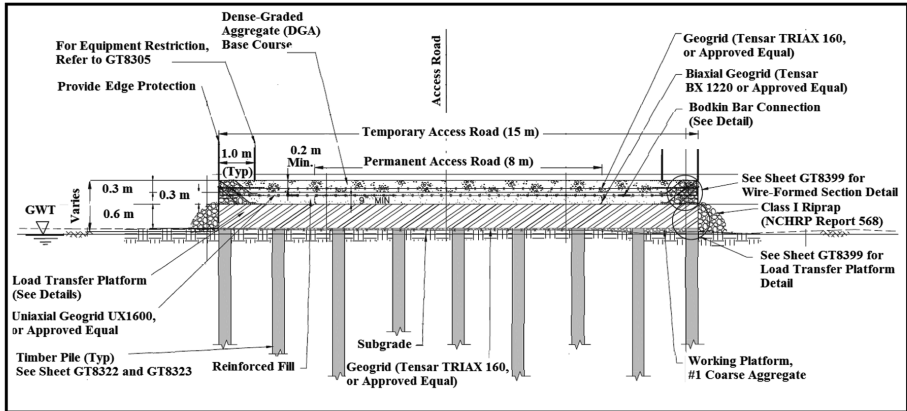
Fig. 2. Configuration of geogrid-reinforced-earth pile-supported embankment

Fig. 3. Aerial photo of the proposed geogrid-reinforced-earth pile-supported embankment after construction

3 Design Loads and Analysis of Proposed Embankment

In this section, design loads considered in the analysis and design of the proposed geogrid-reinforced pile-supported embankment are presented.

3.1 Design Loads for the Proposed Embankment

A design live load for the embankment was considered in accordance with AASHTO LRFD HL-93 Vehicular Loading, which includes a design truck having 40 kN front and 160 kN middle and rear axles, or a design tandem having two 125 kN axles superimposed on 10 kN/m line load. Also, a design live load of 12 kN/m^2 was used to evaluate the stability of embankments. The embankment was also checked for a live load that includes Manitowoc 2250 Series 3, Liebherr 1300SX, and Liebherr 895 cranes with maximum traveling and pick pressures (under 1.2-m-wide by 9-m-long tracks) of 325 kN/m^2 and 425 kN/m^2, respectively. A 1.5 m minimum clear distance between the edge of the embankment and the edge of equipment tracks was assumed to be kept at all times.

3.2 Design Soil Parameters

Field and laboratory tests were performed to estimate design soil parameters for different soil layers encountered during the subsurface investigation. Lab tests performed on soil samples extracted from the organic clay and peat included Atterburg limits, natural water content, strength (triaxial and torvane) and consolidation testing. For the organic clay and peat, index tests indicated natural water contents typically ranging from 90% to 110% and liquid limits typically ranging from 100% and 110%. Strength tests indicated the undrained shear strength of the organic clay/peat ranged from 5 to 25 kN/m^2. Because the shear strength and consolidation of the organic clay and peat layers control the behavior of the proposed embankment, it was decided to build and monitor a grade-supported test embankment to either confirm or modify strength and consolidation parameters from lab tests, based on field observations. The performance monitored for the test embankment, including embankment settlement and porewater pressure within organic clay and peat, agreed well with the embankment performance predicted based on soil parameters obtained from lab tests. The design soil parameters for the reinforced fill, existing fill, organic clay, peat, marine sand, and glacial till layers are given in Table 1.

3.3 Finite Element Analysis and Material Modeling

An initial design of the embankment was performed following the soil arching model presented by Carlsson (1987). A typical allowable axial compressive capacity of 300 kN per timber pile was used to evaluate pile spacing. Pile length was determined in such a way to keep minimum 3 m embedment into natural marine sand and/or glacial till soils. A finite element (FE) model was then built to simulate, and analyze the construction and the behavior of the embankment under various design loading scenarios. The analysis was performed using the commercial computer code Plaxis 2D. The embankment and underlying soils were idealized using 15-node, 2D plane-strain elements. The behavior of different soils was idealized as elasto-plastic materials with reinforced fill, existing fill, marine sand, and glacial till soils modeled as Mohr-Coulomb materials, and the organic clay and peat obeying the soft-soil-creep model. The timber piles were modeled as embedded pile elements and the geogrid reinforcement was modeled as elastic membrane. The FE model used to analyze the geogrid-reinforced-earth pile-supported embankment is shown in Fig. 4.

Table 1. Material models and design soil parameters

A - Strength and deformation parameters:

Material	Unit weight (kN/m^3)	Soil model	Phi (Deg.)	S_u (kN/m^2)	E (kN/m^2)	v
Reinforced fill	19	Mohr-Coulomb	30	N/A	4×10^4	0.3
Existing fill	19	Mohr-Coulomb	30	N/A	2×10^4	0.3
Organic clay	14	Soft Soil Cr Model	N/A	7.5 to 17.5	N/A	0.45
Peat	12	Soft Soil Cr Model	N/A	12.5	N/A	0.45
Glacial till and marine sand	19	Mohr-Coulomb	30	N/A	6×10^4	0.35

B - Consolidation parameters:

Material	C_c	C_r	K_x (m/s)	K_x/K_y	Remarks
Organic clay	0.2	0.02	1.8×10^{-7}	5	Estimated based on data from monitored embankment section.
Peat	0.3	0.03	1.8×10^{-7}	5	

Phi = Angle of Internal Shearing Resistance

S_u = Undrained Cohesion

E = Elasticity Modulus

v = Poisson's Ratio

C_c = Compression index

C_r = Re-compression index

Kx = Permeability in horizontal direction
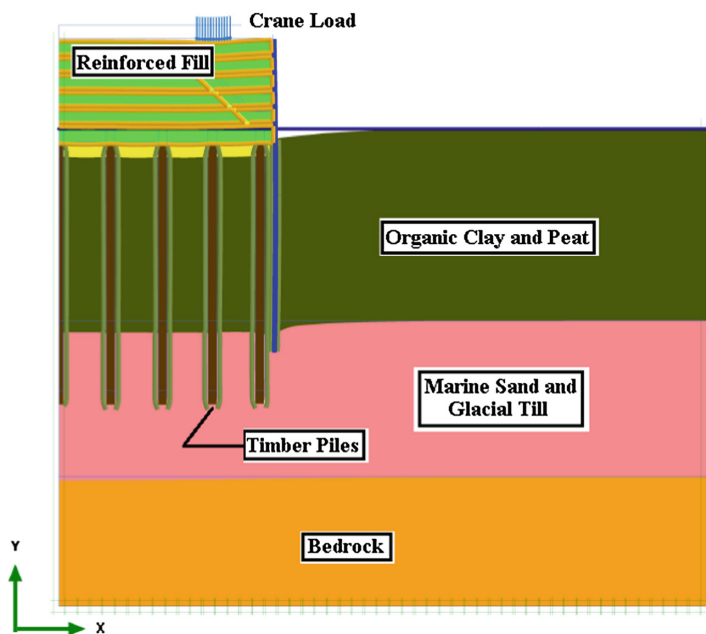
Ky = Permeability in vertical direction

Fig. 4. FE model used to analyze the geogrid-reinforced-earth pile-supported embankment

3.4   Staged Construction and Stability Analysis of Proposed Embankment

The FE model described above was used to simulate the construction and operation of the proposed embankment using the Plaxis built-in staged-construction procedure. Construction stages simulated included installation of timber piles, building the initial load-transfer platform (LTP), building the geogrid-reinforced fill embankment and applying the embankment loads. After construction stages were simulated, the strength reduction method (SRM) was utilized to evaluate the embankment stability against different potential failure modes as defined by either local overstress or excessive deformation in the geogrid reinforcement, piles, and/or soft organic clay and peat soils due to loads directly transmitted to these elements.

3.5   Analysis Results and Design Case

Analysis results obtained from the FE model included deformations, stresses and forces. The results were obtained for each simulated construction stage and for the cases of the embankment being utilized as a temporary access road supporting heavy cranes, and as a permanent access road supporting bridge maintenance equipment. For the case of embankment under temporary crane loadings, Figs. 5 through 7 show results of vertical displacements of the entire FE mesh, effective vertical stresses on a horizontal plane immediately above heads of timber pile, and axial forces in the
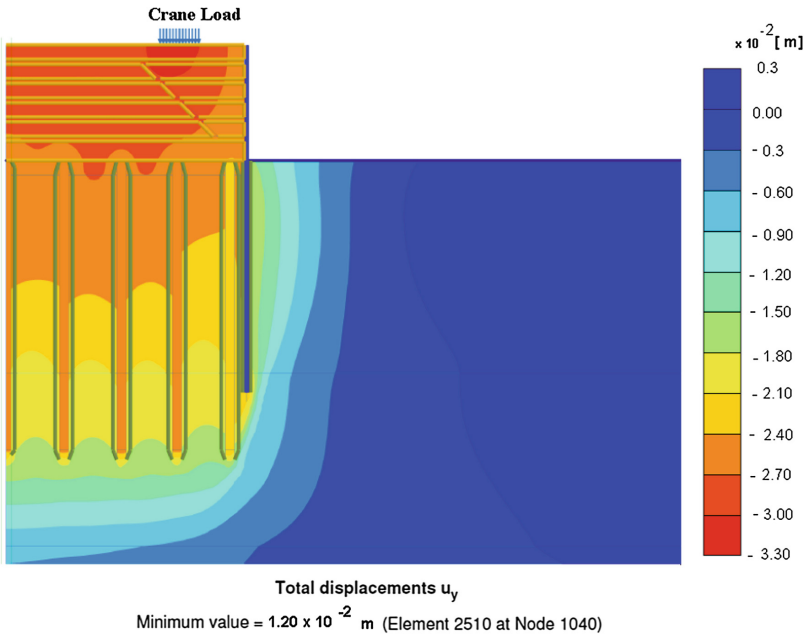

Fig. 5. Distribution of vertical displacement as predicted from FE analysis for the reinforced-earth embankment and underlying soils and piles

geogrid immediately above the timber piles. The FE analysis done with different pile spacing and different LTP geogrid stiffness indicated that the pile spacing as well as the stiffness of the geogrid reinforcement in the LTP (i.e. the number of geogrid layers x the single-layer stiffness) control the pressures imposed by the embankment on the underlying soil subgrade. Various runs were performed to reach a geogrid stiffness that resulted in minor pressure on the soil subgrade (i.e. maximum load shared by piles) while keeping pile spacing within 1.5 to 2.5 m and pile load within 300 kN per pile. The results of the FE analysis indicated the embankment behaves as a reinforced-earth mat transferring the majority of the embankment loads to the timber piles. This behavior is evident from the distribution of the vertical effective stresses (Fig. 6) on a horizontal plane immediately above timber pile heads. Such behavior resulted in minimizing embankment settlement and indicated successful embankment design.
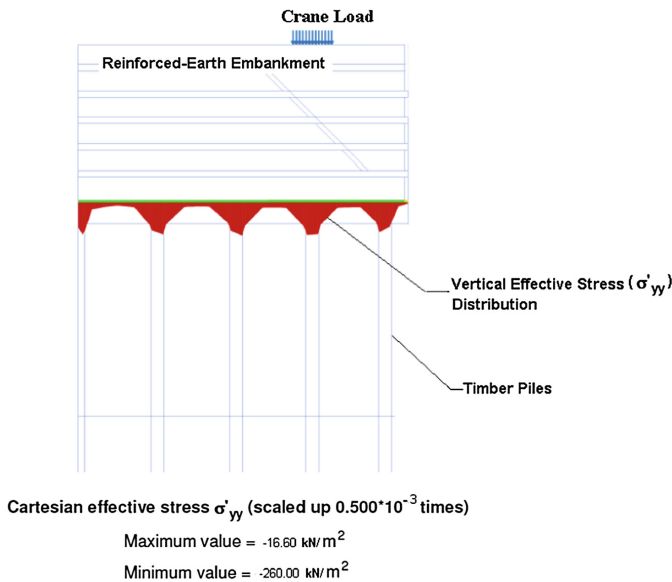

Cartesian effective stress σ'_{yy} (scaled up $0.500*10^{-3}$ times)

Maximum value = -16.60 kN/m^2

Minimum value = -260.00 kN/m^2

Fig. 6. FEA-predicted vertical effective stresses on horizontal plane immediately above timber piles

4 Embankment Construction and Performance

Figure 8 shows the timber pile installation for the proposed reinforced-earth pile-supported embankment. Because of the very soft nature of the organic clay and the peat encountered at some sections along the embankment profile, a layer of tri-axial geogrid with geotextile and granular fill was placed on top of the natural soil subgrade, to create a stable working platform for the pile installation equipment. After finalizing timber pile installation for each embankment segment, the geogrid-reinforced load-transfer platform was installed and the construction of the geogrid reinforced embankment was completed. The stiffness and strength of the geogrid was also designed in such a way to minimize load transfer to underlying soil subgrade.
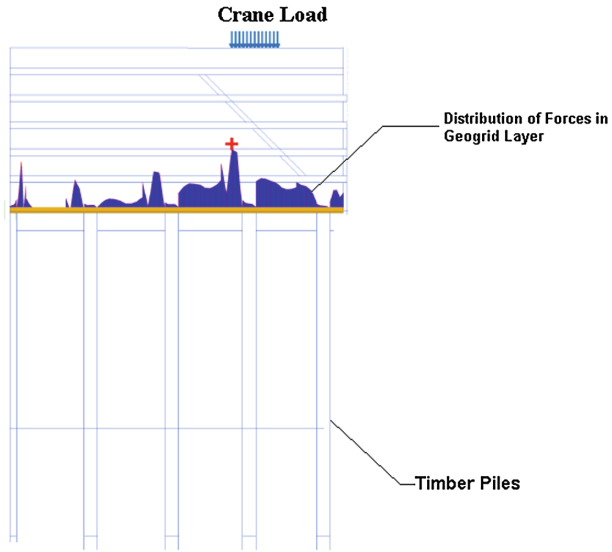
Fig. 7. FEA-predicted axial forces in the geogrid layer above timber piles

Fig. 8. Installation of timber piles during the construction of the geogrid-reinforced pile-supported embankment

Fig. 9. Geogrid-reinforced pile-supported embankment during operation

The critical case of loading resulted from the operation of the heavily loaded Liebherr 895 cranes while picking, see Fig. 9. The heavily loaded Liebherr 895 cranes were equipped with sensors to automatically stop crane operation in case the angular distortion resulting from ground differential settlement underneath any two points on the crane track exceeded a triggering limit. A timber mat was placed on top of the embankment to distribute the crane track load over the top of the embankment and to minimize differential settlement and angular distortion under the crane track. When subject to heavily loaded crane operations, the geogrid-reinforced-earth pile-supported embankment performed very well, and no differential settlement that required halting crane operation was observed under the crane track, as evidenced by the sensors attached to the crane.

5   Conclusions

The design and construction of a geogrid-reinforced pile-supported embankment was presented in this paper. Because of the complex behavior of the geogrid-reinforced embankment, the analysis of the embankment was performed utilizing finite element method. Subsurface investigation including field and lab testing was done before design starts. However, because of challenging geotechnical conditions encountered at the project site, a test embankment was built and monitored, and the monitoring results of the test embankment confirmed the design soil parameters obtained from lab tests. Results of numerical analysis indicated effectiveness of the proposed design of the geogrid-reinforced piled embankment. Settlements obtained from the numerical analysis indicated acceptable

total and differential settlement of the embankment under heavily loaded crane operation, which agreed well with the embankment performance monitored during crane operation. Pile loads obtained based on the results of FEA indicated the Carlsson (1987) approach overestimated load share transmitted to piles, possibly because of Carlsson's approach ignores the effect of the geogrid stiffness and the soil-geogrid-pile interaction. The use of the FEA, rather than conventional analysis approaches, enabled performing full soil-geogrid-pile interaction and, hence, optimizing the geogrid stiffness. In addition, the use of the geogrid-reinforced LTP with optimized stiffness in combination with timber piles resulted in larger pile spacing and, hence, reduced the cost of the required piling.

References

Bhasi, A., Rajagopal, K.: Numerical modeling and analysis of geosynthetic reinforced pile supported embankments. In: Proceeding of the 5th WSEAS International Conference on Engineering Mechanics, UK, February 2012 (2012)

Byrum, C.R.: Analysis of pile supported embankments considering soil settlement and load transfer platform strain compatibility. Journal of the Transportation Research Board: Paper No. 15-2458 (2014)

Poulos, H.G.: Design charts for piles supporting embankments on soft clay. ASCE J. Geotech. Geoenviron. Eng. **133**(5), 493–501 (2007)

Briançon, L., Faucheux, G., Andromeda, J.: Full-scale experimental study of an embankment reinforced by geosynthetics and rigid piles over soft soil. In: Proceeding of EuroGeo, Scotland, September 2008 (2008)

Carlsson, B.: Reinforced Soil, Principles for Calculations: Terratema AB, LinkOping (in Swedish) (1987)

Navin, M.P.: Stability of embankments founded on soft soil improved with deep-mixing-method columns. Ph.D. dissertation, Virginia Polytechnic Institute and State University – The United States (2005)

van Eekelen, S.J.M., Bezuijen, A., van Tol, A.F.: Validation of analytical models for the design of basal reinforced piled embankments. Geotext. Geomembr. **43**, 56–81 (2015). www. elsevier.com/locate/geotexmem

Satibi, S., van der Meij, R., Leoni, M.: Piled embankments: literature review and required further research using numerical analysis. Institutsbericht 34, Institute for Geotechnical Engineering, University of Stuttgart, Germany (2007)

Svanø, G., Ilstad, T., Eiksund, G., Want, A.: Alternative calculation principle for design of piled embankments with base reinforcement. In: Proceeding of the 4th International Conference on Ground Improvement Geosystems, Helsinki, June, pp. 541–548 (2000)

Zhuang, Y., Cui, X.: Reinforced piled embankment for a high-speed railway over soft soil: a numerical and analytical investigation. Acta Geotech. Slov. **2**, 57–65 (2015)