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NUMERICAL ANALYSIS OF GEOSYNTHETIC-RAMMED AGGREGATE PIER SUPPORTED EMBANKMENTS

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ABSTRACT

This paper presents results from numerical study to investigate the interactions between rammed aggregate piers and geosynthetic reinforcement in pier-supported embankments. The investigation was conducted using a two-dimensional, plane-strain, finite element model. Linear elastic, perfectly plastic constitutive model parameters were assumed for the rammed aggregate piers, the matrix soil, the embankment fill, and the aggregate blanket. In addition to several pier-soil stiffness ratios considered in the analyses, a range of center-to-center spacings between piers was included. The geosynthetic reinforcement was modeled as a tensile element with various tensile stiffness values. Results obtained from this study provide insight into: (1) the interaction between the pier elements and the geosynthetic reinforcement to reduce differential settlement; (2) range of stress concentration ratio; and (3) tensile force developed in the geosynthetic reinforcement. It is concluded that the efficiency of using geosynthetic reinforcement is improved as both the geosynthetic modulus and the pier-soil stiffness ratio increase.

INTRODUCTION

Construction of new embankments over highly compressible soils and rapid widening of existing roadways and embankments can create differential settlement problems. One approach to mitigate this problem is to support the embankment on

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driven piles with concrete caps (Han and Gabr 2002). This solution, however, can result in high initial cost and construction constraints.

An alternative approach to using pile caps is to use ground improvement systems, such as stone columns, deep soil mixing, soil cement columns etc. in combination with layers of geosynthetic reinforcement. Recently, rammed aggregate piers have been used to support highways and embankments constructed over soft soils (Lawton et al. 1994, White et al. 2003). Rammed aggregate piers are constructed by ramming successive layers of base-course aggregate in a vertical pre-bored hole. The ramming action, which is facilitated by the use of a beveled tamper, creates relatively stiff vertical inclusions in the matrix soil, that are capable of carrying high foundation loads. The mechanism of load transfer from the embankment body to the foundation system in pile-supported embankments is primarily influenced by the soil arching effect (Terzaghi 1943). In typical pile-supported embankment systems, closely-spaced concrete or timber piles with relatively large pile caps can be effective at controlling differential settlement (Han and Gabr 2002). An alternative solution is the use of geosynthetic reinforcement (i.e., geogrid) to accelerate the construction progress and reduce the cost. Previous numerical studies (Ohkubo et al. 1996, Han and Gabr 2002) have show that geosynthetic reinforcement can enhance the load transfer to supporting piles thus reducing the settlement of the matrix soil.

The role of the geosynthetic reinforcement in embankments supported by rammed aggregate piers is investigated in this study. As a result of the complicated interactions between the geosynthetic reinforcement, rammed aggregate piers, matrix soils and the embankment body, a numerical analysis using finite element method was conducted. This investigation focuses on: (1) the interaction between the piers and the geosynthetic reinforcement to reduce differential settlement; (2) stress concentration on the top of the piers; and (3) tensile force developed in the geosynthetic reinforcement.

NUMERICAL ANALYSIS

Description of the Finite Element Model

The PLAXIS (version 7.2) finite element code was used to model a geosynthetic-reinforced, rammed aggregate pier-supported embankment. A plane-strain, finite element model that consisted of two pier elements, matrix soil, aggregate blanket, embankment fill, and a layer of geosynthetic reinforcement was developed in this study. Pier elements were 0.9 m in diameter and 4.5 m long. The geosynthetic layer was positioned within a 0.45 m thick aggregate blanket directly overlying the pier elements and the matrix soil. The embankment fill of 9.6 m was placed in sixteen equal lifts (i.e., 0.6 m for each lift) above the aggregate blanket.

Input Parameter Values

Four different center-to-center pier spacings, *S*, (1.8, 2.4, 3, and 3.6 m) were considered in this analysis. In addition, a wide range of pier-soil stiffness ratios, *n*, was investigated. The pier-soil stiffness ratio is defined as the ratio of the elastic modulus between the pier material and the matrix soil. For rammed aggregate piers, reasonable pier-soil stiffness ratio may range from 25 to 45 (Lawton 1999). However, pier-soil stiffness ratios ranging from 5 to 80 were selected in this study to account for the variation in the quality of rammed aggregate piers in the field. Moreover, to study the effect of the pier-soil stiffness difference, additional cases in which the pier-soil stiffness ratio was increased up to 100,000 were analyzed. With the exception of the geosynthetic reinforcement, all materials were modeled using elastic perfectly-plastic constitutive parameters. For *n* values greater than 80, linear elastic without provision for plasticity model was assumed for pier elements to avoid local failure due to highly concentrated stresses at the top of the piers. The geosynthetic reinforcement was modeled as a "geotextile" element, which solely carries tensile forces.

In PLAXIS, a secant modulus (E_{50}) is used instead of the initial modulus (E_i). Secant modulus is calculated at 50 percents of the peak deviator stress of the stress-strain curve. Table 1 presents the input parameter values for all materials used in this analysis. For *n* values less than 80, the matrix soil modulus values were calculated by dividing the modulus of the compacted aggregates by the corresponding pier-soil stiffness ratio, *n*. White et al. (2002) reported the secant modulus of compacted aggregates of 96,000 kPa as determined from triaxial compression tests at a confining pressure of 100 kPa (Fig. 1). For *n* values greater than 80, the modulus of the soil is assumed to be equal to 1200 kPa and the modulus of the piers is calculated as the product of the soil modulus and the corresponding pier-soil stiffness ratio. Properties of the geosynthetic reinforcement were modeled after Tensar BX6200 with tensile modulus, *J*, of 76 kN/m based on the creep limited strength of 3.8 kN/m at 5% strain. To investigate the influence of the geosynthetic modulus, additional cases in which the tensile modulus of the geosynthetic was higher than 76 kN/m were analyzed. The geosynthetic-soil interface was modeled assuming a rigid contact (i.e., no shear strength reduction) between the geotextile and the soil.

TABLE 1. Input Parameter Values for the Finite Element Model

Property	Pier Elements	Matrix Soil	Blanket	Fill
Elastic Modulus, E (kPa)	96,000 ($n \leq 80$) 1200n* ($n > 80$)	96,000/n* ($n \leq 80$) 1200 ($n > 80$)	12,000	9,600
Poisson's Ratio, u	0.4	0.3	0.4	0.3
Friction Angle, ϕ' (degrees)	48	25	30	25
Cohesion, c' (kPa)	25	0	0	0

**Note: n = pier-soil stiffness ratio*

Because of the plane strain boundary condition, the model considers the pier element as a trench with the width equal to the pier diameter. It was assumed that the weighted average stiffness of the piers and matrix soil between piers in the perpendicular dimension was equal to the stiffness of the trench. The expression derived for calculating the "equivalent" modulus of the trench for a square pattern is as follows:

$$E_{eq} = \frac{E_g A_g + E_s A_s}{A_t} = E_g \left[\frac{\pi D}{4S} \left(1 - \frac{1}{n} \right) + \frac{1}{n} \right] \quad (1)$$

where E_g is the modulus of the pier, E_s is the modulus of the matrix soil (i.e., E_g/n), D is the pier diameter, A_g, A_s, and A_t are the pier, soil, and trench areas, respectively. The initial stress condition for all cases was set at $K_o = 1.0$, which yielded a zero shear stress state on all finite elements prior to the surcharge load from the embankment fill.

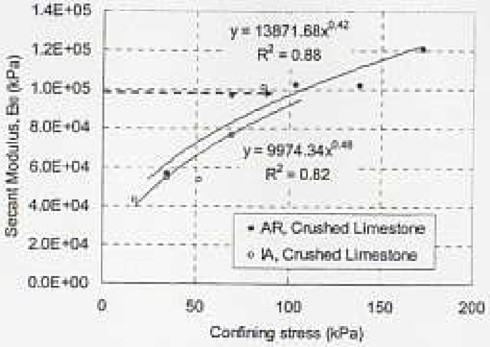

FIG. 1. Secant Modulus of Compacted Aggregates (White et al. 2002)

RESULTS AND DISCUSSIONS

Settlement Predictions

Figures 2 shows the differential settlement between the matrix soil and the rammed aggregate piers at maximum fill height (9.6 m) for both geosynthetic reinforced and unreinforced cases. The minimum differential settlement was only about 2 mm for pier-soil stiffness ratio of 5 and spacing of 1.8 m; whereas, the maximum differential settlement was 61 mm for pier-soil stiffness ratio of 80 and spacing of 3.6 m. The increase in differential settlement as the pile spacing increases was also reported in Ohbuko (1996). For pier-soil stiffness ratios less than 80 (Fig. 2), the calculations indicate that the geosynthetic reinforcement has no significant influence on differential settlement reduction. In the authors' opinion this is a result of a combination of interrelated factors including: (1) relatively low differential settlement between the pier elements and the matrix soil; (2) relatively low tensile modulus of the geosynthetic reinforcement; and (3) relatively low pier-soil stiffness ratios. As shown in Fig. 3, the effectiveness of geosynthetic reinforcement for reducing differential settlement increases as the pier-soil stiffness ratio increases up to 1000.

Stress Concentration

Stress concentration ratio, which is defined as the ratio of the average axial stress on top of the pier elements to the average axial stress applied to the matrix soil, has been used as a global index that incorporates the effects of soil arching, tension membrane, and pile-soil stiffness difference (Han and Wayne 2000). Figure 4 presents the stress concentration ratio as a function of pier spacing and pier-soil stiffness ratio. As can be seen, the stress concentration ratio increases as the pier spacing is decreased and the pier-soil stiffness ratio is increased.

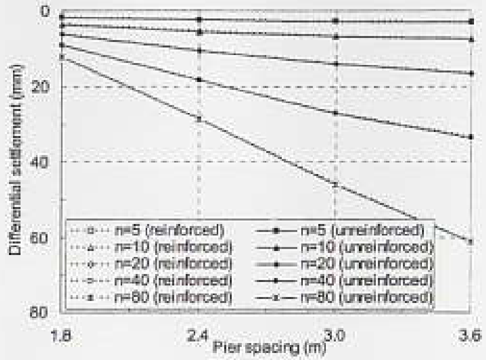

FIG. 2. Differential Settlement of Reinforced Case (J=76 kN/m) versus Unreinforced Case

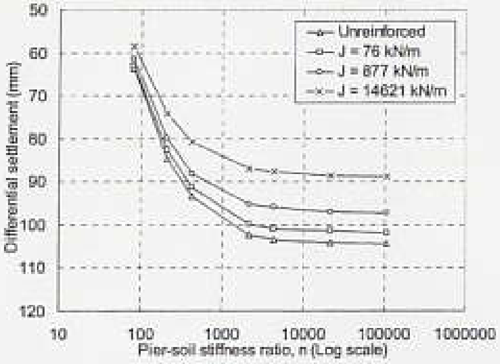

FIG. 3. Differential Settlement as a Function of Geosynthetic Modulus and Pier-Soil Stiffness Ratio (S = 3 m)

Figure 5 indicates that the stress concentration ratio depends on the pier-soil stiffness ratio and the modulus of the geosynthetic reinforcement. It is also shown that the stress concentration ratio increases as the the pier-soil stiffness ratio increases up to 1000. Han and Gabr (2002) obtained a similar trend in stress concentration ratio with increasing pier-soil stiffness ratios. Table 2 summarizes the analysis results obtained from several previous studies.

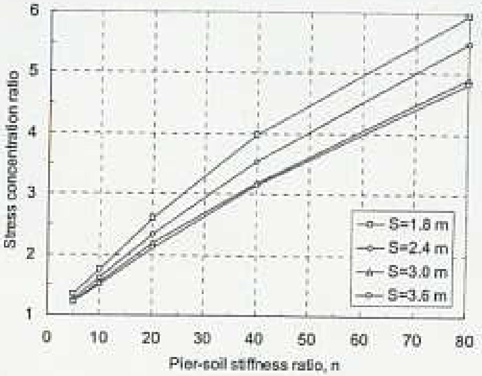

FIG. 4. Stress Concentration Ratio for Pier Spacing (J=76 kN/m)

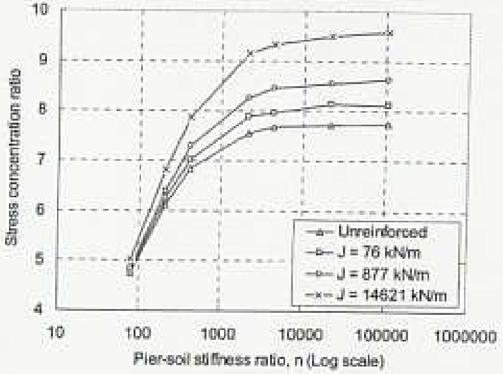

FIG. 5. Stress Concentration Ratio as a Function of Geosynthetic Modulus and Pier-Soil Stiffness Ratio (S = 3 m)

Tensile Stress Development in the Geosynthetic Reinforcement

Figure 6 presents the maximum tension developed in the geosynthetic reinforcement at different pier-soil stiffness ratios and spacings at maximum embankment height (9.6 m). For n values less than 80, the maximum tensile force in the geosynthetic reinforcement was about 3.3 kN/m, which is less than the assumed creep limited strength of 3.8 kN/m at 5% strain. It is also indicated in Fig. 6 that the tensile force developed in thegeosynthetic reinforcement increases with the pier-soil stiffness ratio and the pier spacing. The strain in the geosynthetic reinforcement calculated near the edges of the pier elements was about 4.3% at the maximum embankment height for pier-soil stiffness ratio of 80 and the spacing of 3.6 m. However, strains calculated at other sections of the geosynthetic reinforcement with different pier-soil stiffness ratios and spacings were mostly less than 1%. Tensar (2002) reported "true" modulus values of 320 KN/m and 270 KN/m, attained at 1% and 2% strains respectively, for BX6200 geogrid. These values are more than triple the modulus value used in the analysis.

TABLE 2. Comparison of Analysis Results from Previous Studies

References	Determination of SCR*	Pile Type	Pile-soil Stiffness Ratio, n	Geogrid Modulus, J (kN/m)	Differential Settlement (mm)	Range of SCR*
Maddison et al. 1996	Direct measurement	Vibro-concrete columns	–	31.5	5	8 to 13
Han and Gabr** 2002	Numerical analysis	Single concrete pile	10 to 80	$8.6\text{x}10^2$	75 to 125	7.5 to 15
This Paper	Numerical analysis	Rammed aggregate piers	5 to 80	76	2 to 105	1.2 to 6

* SCR = stress concentration ratio

** analysis performed for n from 10 to 10^4, J from 0 to $8.6\text{x}10^2$ kN/m

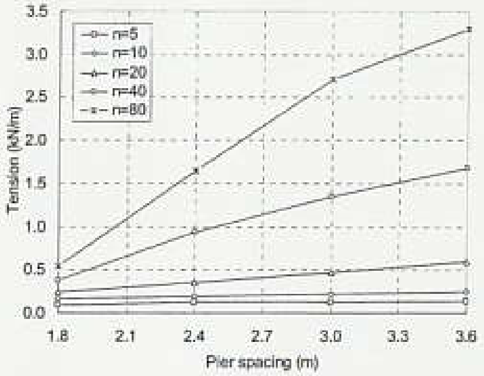

FIG. 6. Tension in the Geosynthetic Reinforcement versus Pier Spacing

CONCLUSIONS

Based on the input parametric values used in this study, it is concluded that the geosynthetic reinforcement provides limited improvement to the rammed aggregate pier-soil reinforcement system for the application of differential settlement control. Results obtained from this study also indicate that the use of the geosynthetic reinforcement in pier-supported embankments is more effective when pier-soil stiffness ratio, *n*, is higher than 1000. Strains developed in the geosynthetic reinforcement in rammed aggregate pier-supported embankments are much less than the assumed value of 5%. Accordingly, it is suggested that a higher modulus for the geosynthetic reinforcement or multiple layers should be considered in future studies.

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REFERENCES

Han, J., and Gabr, M. A. (2002). "Numerical analysis of geosynthetic-reinforced and pile–supported earth platforms over soft soil." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 128 (1), 44-53.

Han, J., and Wayne, M. (2000). "Pile-soil-geosynthetic interaction on geosynthetic reinforced/piles embankments over soft soils." *Presentation and CD-Print at the 79th Annual Transportation Research Board Meeting*, Washington D.C., Paper No. 000777.

Lawton, E. C., Fox, N. S., and Handy, R. L. (1994). "Control of settlement and uplift of structures using short aggregate piers." *In-situ Deep Soil Improvement*, ASCE, 121-132.

Lawton, E. C. (1999). "Performance of Geopier foundations during simulated seismic tests at South Temple bridge on Interstate 15, Salt Lake City, Utah." *Interim Report No. UUCVEEN 95-O5*, University of Utah, Salt Lake City, UT, USA.

Maddison, J. D., Jones, D. B., Bell, A. L., and Jenner, C. G. (1996). "Design and performance of an embankment supported using low strength geogrids and vibro concrete columns." *Proceedings of Geosynthetics: Applications, Design and Construction*, De Groot, Den Hoedt, and Termaat, eds., Balkema, Rotterdam, 325-332.

Ohkubo, T., Asada, S., and Karube, D. (1996). "A study on the reinforcing effects of geogrids overlaid on pile group for the embankment foundations." *Earth Reinforcement*, Balkema, Rotterdam, 641-646.

Tensar® Earth Technologies, Inc. (2002). "Specification for structural geogrid." *http://www.tensarcorp.com/download/ps_bxux6.02.doc.*

Terzaghi, K. (1936). "Stress distribution in dry and in saturated sand above a yielding trap-door." *Proceedings of the 1st International Conference on Soil Mechanics*, Cambridge, Massachusetts, 307-311.

White, D. J., Suleiman, M. T., Pham, H. T. V., and Bigelow, J. (2002). "Constitutive equations for aggregates used in Geopier® foundation construction." *Report Prepared for the* Geopier® *Foundation Company, Inc.*, Iowa State University, Ames, IA, USA.

White, D. J., Gaul, A. J., and Hoevelkamp, K. (2003). "Highway applications for rammed aggregate pier in Iowa soils." *Final report, Iowa DOT TR-443.*