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Numerical simulation and sensitivity analyses of full-scale test embankment with reinforced lightweight geomaterials on soft Bangkok clay

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ABSTRACT

A full-scale test embankment was constructed on soft Bangkok clay using rubber tire chip–sand mixture as a lightweight geomaterial reinforced with geogrid under working stress conditions. The facing of the embankment was made of segmental concrete blocks with rock filled gabion boxes as the facing to the sloping sides. This paper attempts to simulate the behavior of the full-scale test embankment using PLAXIS finite element 2D program by means of undrained analysis in the construction stage and thereafter consolidation analysis was performed during the service stage. The settlement predictions of the soft clay foundation mostly depended on the assumed thickness of the weathered crust and the OCR values of the soft clay layer. The predicted excess pore water pressures were sensitive to the OCR values of the soft clay layer. The lateral wall movements were overpredicted by the analysis due to the partially drained consolidation process at the early stage of the construction. The FEM computed geogrid movements were smaller than the observed field data due to the use of lightweight tire chips-sand backfill. The maximum tension line agreed reasonably well with the coherent gravity bilinear failure plane. The sensitivity analyses of settlements, excess pore water pressures, lateral wall movements, geogrid movements and tensions in geogrid were performed by varying the weathered crust thickness, the OCR values of soft clay, the permeability values of the soft clay and the interface coefficient of the geogrid. The settlements and the excess pore water pressures changed significantly when the OCR and the permeability values of soft clay were varied. The interface coefficient of the geogrid reinforcements affected the lateral wall movements, geogrid movements and tensions in the geogrids. The higher interface coefficient yielded less wall/geogrid movement and resulted in higher tensions in geogrids as expected. The results of analyses show that the FEM analysis using 2D plane strain conditions provided satisfactory predictions for the field performance.

1. Introduction

Geosynthetic-reinforced segmental retaining walls/embankments have been well accepted in practice as alternatives to conventional retaining structures; their benefits include sound performance, aesthetic appearance, cost effectiveness and expediency of construction. This is especially true in soft ground area such as Bangkok, Thailand. Although many geosynthetic-reinforced soil walls have been safely constructed and are still performing well, there are many areas such as alluvial clay or soft clay area that need in-depth studies in order to better understand the mechanical behavior of this system under more aggressive and harsh environments (Yoo and Song, 2006). Issues related to the design and factors affecting the performance of reinforced soil have been addressed by many researches in recent times (e.g. Bathurst et al., 2005; Park and Tan, 2005; Skinner and Rowe, 2005b; Al Hattamleh and Muhunthan, 2006; Hufenus et al., 2006; Nouri et al., 2006; Chen and Chiu, 2008). Also, the behavior of reinforced earth structures has been comprehensively studied through field observations of full-scale physical model, laboratory model testing, and numerical simulation (Bergado et al., 1995, 2000, 2003; Frankowska, 2005; Varuso et al., 2005; Bergado and Teerawattanasuk, 2007; Hatami and Bathurst, 2005, 2006; Ling and Leshchinsky, 2003; Won and Kim, 2007). The use of geosynthetic-reinforced subgrade, railway and pile support embankment is studied by many researchers such as Frankowska (2007), Brown et al. (2007) and Min et al. (2007). Chen et al. (2007) conducted a series of centrifuge modeling test of a geotextile-reinforced wall to study its behavior in wet state due to poor drainage conditions. The study of Sarsby (2007) concerns the use of 'Limited Life Geotextiles' (LLGs) which are designed on the basis of having a limited working life as

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basal reinforcement for an embankment built on soft clay. An alternative method such as numerical or simulation by means of appropriate methods such as finite element (FE) (e.g. Basudhar et al., 2008) or finite-difference (FD) techniques (e.g. Ho and Rowe, 1994) is essentially required for a better understanding of the mechanical response of reinforced soil walls subjected to different loading conditions to develop more advanced design methodologies compared to the current limit equilibrium-based approaches. A strategy to meet this goal is to investigate the performance of reinforced soil walls using numerical models validated against physical data gathered from field or laboratory model (Hatami and Bathurst, 2006). Most researchers have assumed plane strain condition for numerical simulations of reinforced earth structures (Chai, 1992; Chai and Bergado, 1993a,b; Bergado et al., 2000, 2003; Karpurapu and Bathurst, 1995; Alfaro et al., 1997; Rowe and Ho, 1998; Rowe and Li, 2002; Hinchberger and Rowe, 2003). Recently, Skinner and Rowe (2005a) have presented the results of a numerical investigation into the bearing capacity stability of geosynthetic-reinforced retaining walls constructed on yielding foundations. Skinner and Rowe (2005b) also performed a numerical investigation into the long-term effect of foundation yielding on a geosynthetic-reinforced retaining wall and bridge abutment, to examine both the internal and the external stability of the wall.

Hatami and Bathurst (2005) reported a survey of published work on numerical simulation of reinforced soil walls and categorized this work according to: (1) whether numerical models were verified against experimental/field evidence or were simply idealized model; (2) size of the experimental models used for the verification of the numerical models; (3) quality and extent of the measured data reported for each experimental/field case; (4) assessment of the accuracy of the physical data; (5) simulation of the construction sequence and the compaction effects; (6) constitutive models for the soil backfill and the availability of laboratory data from which model parameters can be selected; and (7) consideration of load–strain–time effects on the mechanical behavior of polymeric reinforcement layers. Hatami and Bathurst (2005) concluded that validation of numerical models was deficient with respect to many of the issues identified previously. Ideally, a numerical model should be robust enough to capture qualitatively and quantitatively the isolated influence of each wall component as it is varied between otherwise identical structures.

Previous simulations of reinforced walls/embankments on soft Bangkok clay were steel grid reinforced wall with poor quality backfill and wrapped up facing (Bergado et al., 1995), hexagonal wire reinforced wall with sand backfill and gabion facing (Bergado et al., 2000) and hexagonal wire reinforced wall with sand backfill and precast concrete facing panels (Lai et al., 2006). The conclusions of these 2D plane strain studies were that the response of reinforced embankments was principally controlled by the interaction between the reinforcement and the backfill and therefore appropriate model and interface properties were needed; the permeability of the foundation soil influenced the finite element analysis; the embankment loading during the construction stage needed to be modeled appropriately and numerical analysis yielded better predictions of performance than the analytical models. Chai and Bergado (1993a) used finite element method to analyze geogrid reinforced embankments on soft clay and conclude that the stage construction of embankment on soft ground can be simulated by finite element analysis considering the large deformation phenomenon and the variation of the foundation permeability during consolidation.

This paper deals with the predictions, numerical simulations and sensitivity analyses of the performance of a fully instrumented full-scale test embankment constructed on soft Bangkok clay using lightweight rubber tire chips-sand backfill with geogrid reinforcements. A commercially available finite element program was used to predict the performance of the test embankment during construction and post construction stages.

2. Full-scale test embankment

2.1. Subsoil investigation

The test embankment was constructed on the campus of the Asian Institute of Technology (AIT). The general soil profile consists of weathered crust layer of heavily overconsolidated reddish brown clay over the top 2.5 m. This layer is underlain by soft grayish clay down to about 8.0 m depth. The medium stiff clay with silt seams and fine sand lenses is found between the depths of 8.0 and 10.5 m. Below this layer is the stiff clay layer. Fig. 1 summarizes the subsoil profile and the relevant parameters. Soil samples were obtained from the borehole at the construction site down to a depth of about 8 m, the bottom of the soft clay layer. Index tests and consolidation tests were performed on the subsoil samples. The in-situ strength of the subsoil was measured by field vane shear test.

2.2. Embankment construction

Lightweight geomaterials made of rubber tire chip–sand mixture were used as the backfill to alleviate large settlement problems in the soft ground area. The soil reinforcement comprised of polyester (PET) geogrid reinforcement material. The geogrid used in the field consisted of highly molecular, high-strength polyester yarns knitted to stable network and equipped with a polymeric coating protection. The facing components were made of segmental concrete block which measured $0.30 \times 0.30 \times 1.00$ m in dimension.

The rubber tire chips were mixed with sand in the ratio of 30:70 by weight. The vertical spacing of the geogrid reinforcement was 0.60 m. The backfill was compacted in layers of 0.15 m thickness to a density of about 95% of the Standard Proctor density. The compactions were carried out with a roller compactor but near the instrumentation such as the settlement plates, the standpipes and the inclinometer a hand compactor was used. The degree of compaction and the moisture content were checked regularly at several points with a nuclear density gauge. Wherever the degree of compaction was found to be inadequate, additional compaction was done until the desired standards were met. A sand layer was used as the surface cover for the rubber tire chips–sand mixture for reducing the self-heating reaction. The thickness of the sand cover was 0.6 m and a non-woven geotextile was used as erosion protection on the side slopes. Hexagonal wire gabions were placed on either sides of the concrete facing along the side slopes. The rate of construction was 1–2 days for a 0.60 m lift; total time spent for embankment construction was 15 days.

2.3. Instrumentation program

The geogrid reinforcement embankment/wall system was extensively instrumented both in the subsoil and within the embankment itself. Since the embankment was founded on a highly compressible and a thick layer of soft clay which would dictate the behavior of the embankment to a great extent, several field instruments were installed in the soft soil layer. The 3D illustration of full-scale field test embankment is shown in Fig. 2. The instrumentation in the subsoil was installed prior to the construction of the embankment and consisted of the surface settlement plates, subsurface settlement gauges, temporary bench marks, open standpipes, groundwater table observation well, inclinometer, dummy open standpipe, dummy surface settlement plate and dummy subsurface settlement gauges