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Stability analyses of a reinforced soil wall on soft soils using strength reduction method

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ABSTRACT

A two-dimensional coupled mechanical and hydraulic finite element (FE) modeling was performed on a 7.6 m high built-to-failure reinforced soil retaining wall (RSW) on very thick soft clay. The observed ground settlement, toe displacements, and the deep-seated global failure of the RSW were well captured with the FE modeling and the Strength Reduction Method (SRM) incorporated in the FE program. The effects of extending, strengthening and stiffening bottom layers of the reinforcement on the stability of the RSW were further investigated by using the calibrated modeling. The results show that the stability of the RSWs on soft soils can be apparently improved by extending the bottom reinforcement layers. By increasing strength and stiffness of reinforcements, fewer bottom reinforcement layers need to be extended to maintain the stability of the structures. There are upper bound strength and stiffness values for a certain length of the extended reinforcements, beyond which the increments of strength and stiffness will have little effect on the stability. Reinforcement strength should be considered in numerical modeling of reinforced soil structures when the reinforcement strength is less than the upper bound value and internal and compound stabilities are concerned. Ignoring reinforcement strength may lead to overestimation of the stability of the structures. For a safe and economical design, RSWs on soft soils can be reinforced with relatively shorter, low strength and stiffness reinforcements at upper layers while with relatively longer, high strength and stiffness reinforcements at bottom layers.

1. Introduction

Reinforced soil retaining walls (RSWs) have been widely used throughout the world since their first emergence in the early 1980s as the structures have many advantages including esthetics, short construction period, good wall stability, cost effectiveness, good seismic response, strong adaptability on highly compressible soft foundation soil, and the ability to tolerate large differential settlement (Tatsuoka et al., 1997; Bloomfield et al., 2001; Yoo and Jung, 2004).

The limit equilibrium method (LEM) has been used for decades to design major geotechnical structures (e.g. slopes, embankments, pits) and is favored by engineers due to its simplicity. LEM has been also recommended to evaluate the stability of RSWs (BS8006, 1995; AASHTO, 1996, 2002; FHWA, 1996, 2009; NCMA, 1997, 2010). The RSWs on soft clay may suffer large deformation and incur compound or global failure if the shear strength in the subsoil is not large enough. Usually, staged-loading method is employed for the construction of these structures to speed up the consolidation and thus improve shear strength in soft subsoil. However, the increase of soil strength due to consolidation during the loading process cannot be readily considered in LEM, thus it is mainly used to assess the short-term (undrained) stability of the structures on soft clay (Rowe and Li, 2005). Yet the soil hardening during consolidation can be considered and manually increased as an input in LEM (Leroueil et al., 2001; Suzuki and Yasuhar, 2007). Chen et al. (2014) analyzed a geogrid reinforced wall on soft clay with LEM by manually increasing the soil strength in the drained zone, and the obtained factor of safety (FS) is quite comparable with the result from FEM using hardening soil model. The strength reduction method (SRM) was first used for slope stability analysis by Zienkiewicz et al. (1975). Later, it has been applied widely for analyzing slope stability including the computation of factor of safety, especially after the technique was adopted in several well-known commercial geotechnical finite element (FE) or finite difference (FD) programs, e.g. PLAXIS or Fast Lagrangian Analysis of Continua (FLAC) (Cheng et al., 2007; Abusharar and Han, 2011). Some researchers have used the SRM incorporated in FLAC to analyze the stability of reinforced soil slopes and walls. Han et al. (2002) analyzed the stability of unreinforced and geosynthetic-reinforced slopes by using FLAC and obtained FS values similar to those computed by simplified Bishop's method (Bishop, 1955). Leshchinsky and Han (2004) used FLAC to characterize

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the stability of multi-tiered reinforced walls by quantifying the effects of offset distance, fill quality, foundation soil, reinforcement length and stiffness, water, surcharge, and number of tiers. Abdelouhab et al. (2011) analyzed the stability of RSWs with different types of strips using FLAC. Liu et al. (2012) used FLAC to examine the mechanisms and causes contributing to the failure of a high steep geogrid-reinforced slope. As compared with the LEM, the SRM incorporated in FE and FD programs has the following advantages (Dawson et al, 1999; Cala and Flisiak, 2001; Cheng et al., 2007): (1) the critical failure surface is found automatically from the reduction of shear strength; (2) there are no slices, so SRM requires no assumption on the inter-slice shear force distribution; (3) multiple failure surfaces can be obtained; (4) structures (e.g. reinforcements, beams, cables) and interfaces can be included without concerning about compatibility; (5) it is applicable to many complex conditions and can give information such as stress, movements, and pore pressure variation during construction that are not possible in the LEM.

In this study, a 7.6 m high RSW with wrapped-around facing was constructed in stages on very thick soft Shanghai clay (see Fig. 1). A deep-seated global failure was observed during the construction of the RSW (Chen et al., 2014; Xue et al., 2014). The RSW was analyzed by using two-dimensional (2D) coupled mechanical and hydraulic FE package, PLAXIS Version 8.2 (Brinkgreve et al., 2004). The stability of the RSW was examined with the SRM incorporated in the PLAXIS program. The effects of extending, strengthening, and stiffening bottom reinforcement layers on the stability of the RSW were further investigated by using the FE modeling.

2. Description of the RSW project

2.1. Site description

The subsoil profile of the construction site consists of 5 compressible soil layers within the depth of 31 m from the ground level. The 5 soil layers are (from top to bottom): silty clay (2.6 m thick), mucky silty clay (4.4 m thick), clay (3.6 m thick), silty clay (7.4 m thick) and silty clay (13.0 m thick). The soil underneath is a 6.3 m thick stiff clayey silt with average SPT blow count of 31, underlain by stiff silty sand and clay. The ground water table is shallow and fluctuates within 0.5 m below the ground surface. In situ and laboratory tests were conducted on the subsoil samples. Table 1 summarizes the geotechnical properties of the soils.

2.2. RSW construction

The RSW with wrapped-around vertical facing was constructed as a temporary project in Shanghai Botanic Garden, Shanghai, China. The RSW was backfilled as an embankment 37.2 m wide at the top with 1.5H: 1 V side slopes, as shown in Fig. 2(a). Before the construction of the RSW, 1.6 m thick preliminary fill and 0.6 m thick sand cushion were backfilled in sequence above the ground level, as shown in Fig. 2(b). The 1.6 m thick preliminary fill was designed to compensate for the expected foundation settlement to ensure that the RSW did not sink into the subsoil. Then 12 m long prefabricated vertical drains (PVDs) were installed in a triangle pattern with a center to center spacing of 1.5 m. After the settlement caused by the weight of preliminary fill and sand cushion reached stability, the 7.6 m high RSW was then constructed in stages, as shown in Fig. 3.

Fourteen layers of high density polyethylene (HDPE) uniaxial geogrid were placed at a vertical spacing of 0.5 m. Each reinforcement length was 10 m in the horizontal direction with 3.5 m wrapped around segment at the wall facing. The uniaxial geogrid has an axial stiffness of 620 kN/m at 5% strain and a rupture strength of 70 kN/m.

Silty clay excavated from Layer 1 was used as the preliminary fill and the RSW backfill for later vegetation on top of the RSW (embankment). The fill was compacted to a bulk density of 19.0 kN/m^3 by heavy compactors. Medium sand was used for the sand cushion and was compacted to a bulk density of 17.0 kN/m^3.

2.3. Monitoring points

A settlement plate was embedded on the ground surface 4 m behind the wall facing along the centerline of the embankment. A timber target was installed at the RSW toe on the centerline before backfilling. Fig. 2(b) shows the location of the monitoring points. Precise leveling with reference to a benchmark was applied to the displacement measurements in the field.

2.4. Observed ground settlement and failure of the RSW

Fig. 4 illustrates the settlement-time curve obtained from the settlement plate. A sudden settlement occurred on the 190th day when the last 0.9 m thick backfill was emplaced quickly to achieve the finished level of 7.6 m. A subsidence and an arc-shaped crack were observed at the top of the RSW as shown in Fig. 5. The crack was basically located 10 m from the RSW facing, i.e., at the end of the reinforced zone, indicating a deep-seated failure in the RSW. After 9 days, surcharge on the ground in front of the RSW was placed as an emergency measure to prevent further sliding. Subsequently, prestressed concrete pipe piles were installed approximately 5.0 m away from the wall facing. The piles are 0.50 m in diameter and 28 m long, and were installed in a square pattern with a spacing of 3 m. The stabilization was successful after the installation of the piles.

This paper describes the numerical modeling of the RSW performed to simulate the 200 days' construction process of the RSW and the use of SRM to examine the stability of the wall.

3. Numerical modeling

3.1. Conversion of axisymmetric drainage to plane drainage

The actual field consolidation of soil around each drain is close to an axisymmetric condition. To simulate an axisymmetric drainage in plane strain conditions, such as in the 2D FE program, Hird et al. (1995) proposed a geometry and permeability matching equation to convert from axisymmetric to plane strain conditions as follows:

$$k_{hp} = \frac{2}{3} \cdot \frac{B^2}{{D_e}^2} \cdot \frac{1}{\mu} \cdot k_h \tag{1}$$

where k_h = the horizontal permeability of the subsoil; k_{hp} = the equivalent horizontal permeability of the drainage system in plane strain condition; B = the width of the plane-strain unit cell; D_e = the diameter of

Fig. 1. The RSW on soft clay.