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Instability of a geogrid reinforced soil wall on thick soft Shanghai clay with prefabricated vertical drains: A case study

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ABSTRACT

A 7.6 m high geogrid reinforced soil retaining wall (RSW) was constructed at the end of an embankment on very thick, soft Shanghai clay with 12 m deep prefabricated vertical drains (PVDs). The settlement of the ground, the wall movement and pore water pressure were monitored during the construction. From day 118, halfway through the construction, unexpected pore water pressure increment was recorded from the pore water pressure meters installed in the PVD drained zone indicating a possible malfunction of the PVDs due to large deformation in the ground. After the last loading stage, on day 190, a sudden horizontal movement at the toe was observed, followed by an arc shaped crack on the embankment surface at the end of the reinforced backfill zones. The wall was analyzed with a coupled mechanical and hydraulic finite element (FE) model. The analysis considered two scenarios: one with PVDs fully functional, and the second one with PVD failure after day 118 by manually deactivating the PVDs in the FE model. The comparison between the measured and simulated ground settlement, toe movement, and pore water pressure supported the assumption on the malfunction of the PVDs. It is believed that the general sliding failure in the wall was caused by the increase of pore water pressure in the foundation soil and soils in front of the toe. It is suggested that possible failure of PVDs should be considered in the design of such structures, and the discharge rate of the PVDs and the pore water pressure should be closely monitored during the construction of high soil walls on soft soils to update the stability of the structures, especially for grounds where large deformations are expected which may cause the failure of the PVDs.

1. Introduction

Geosynthetic reinforced soil walls (RSWs) have been widely used throughout the world in road embankment and retaining structures. RSWs have many advantages including aesthetics, short construction period, good wall stability, cost effectiveness, good seismic response, strong adaptability on soft highly compressible foundation soils and the ability to tolerate large differential settlement (Tatsuoka et al., 1997; Bloomfield et al., 2001; Yoo and Jung, 2004).

Research has been done on the behavior of RSWs on various soil foundations, and various loading conditions through a large number of in-situ and laboratory tests as well as theoretical analyses (Rowe and Skinner, 2001; Mandal and Joshi, 1996; Viswanadham and Konig, 2009; Leshchinsky and Han, 2004; Yoo and Jung, 2008; Huang et al., 2011; Raisinghani and Viswanadham, 2011). Despite the fact that many geosynthetic-reinforced soil walls have been safely constructed to date, there is limited literature on the performance and behavior of the reinforced soil wall on PVD drained soft soils (Alfaro et al., 1997; Bloomfield et al., 2001; Skinner and Rowe, 2005; Tanchaisawat et al., 2008; Demir et al., 2013), and even fewer reports on failure case studies to a further review of their original design and therefore the failure mechanism (Leonards et al., 1994; Tatsuoka et al., 1997; Collins, 2001; Ling et al., 2001; Borges and Cardoso, 2002; Yoo et al., 2004, 2006; Scarborough, 2005). There are still many areas that need in-depth studies which will help in the safe construction of RSWs on soft clay drained with PVDs (Koerner and Koerner, 2013).

This paper presents a failure case history of a 7.6 m high geogrid-reinforced soil wall with vertical wrap-around facing constructed on a typical Shanghai multi-layer soft soil ground installed with PVDs. Unexpected increase of pore water pressure was observed in the PVD drained soils during the construction, followed by a large deformation in the toe, and an arc shape crack in the surface of the

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embankment at the end of the reinforced zone, indicating the failure of the wall after the last layer of backfill was placed. Numerical modeling was carried out to compare with the in-situ monitored data to identify the failure mechanism of the wall and possible causes of the failure. Recommendations were made at the end for the design and construction of RSWs on soft ground.

2. Description of the RSW project

2.1. Site description

The project was located in Shanghai Botanic Garden, Shanghai, China. The RSW wall is a temporary retaining structure at the end of a 530 m long embankment (see Fig. 1). The embankment is 37.2 m wide on top with a 1.5H: 1V side slope, as shown in Fig. 2 with the ground condition: five layers of soft soils with a total thickness of 31 m from the ground level, which are (from top to bottom): 2.6 m thick of silty clay, 4.4 m thick of mucky silty clay, 3.6 m thick of clay, 7.4 m thick of silty clay and 13.0 m thick of silty clay. Underneath is a layer of 6.3 m thick stiff clayey silt with 31 of average SPT blow count, underlain by stiff silty sand and clay. The ground water table depth is shallow and it fluctuates within 0.5 m below the ground surface. Table 1 summarizes the properties of the subsoil obtained from in situ and laboratory tests.

2.2. RSW construction

The wall was constructed in layers via staged filling. The site was prefilled with 1.6 m thick soil excavated from layer 1 silty clay to compensate the settlement. Above the fill, a 0.6 m thick medium sand was compacted to a bulk density of 17.0 kN/m^3 as a sand cushion for drainage as shown in Fig. 3. Prefabricated vertical drains (PVDs) were installed in a triangle pattern with a spacing of 1.5 m to the depth of 12 m below the surface of the sand cushion. The embankment was constructed using the soil excavated from Layer 1 silty clay compacted at the lift of 20 cm to the bulk density of 19.0 kN/m^3 using a 15 ton static double drum road roller (1.5 m behind the wall face) with compaction width of 2.12 m, and a lightweight walk-behind roller (within 1.5 m from the wall face). The loading stages are shown in Fig. 4.

Fourteen layers of 10 m long high density polyethylene (HDPE) uniaxial geogrid were placed at a vertical spacing of 0.6 m (top 6 layers) and 0.5 m (bottom layers), with 3.5 m of wrap-around segment at the wall facing. The axial stiffness of the geogrid is 620 kN/m at 5% strain and the strength is 70 kN/m.

Fig. 1. The RSW on soft clay.

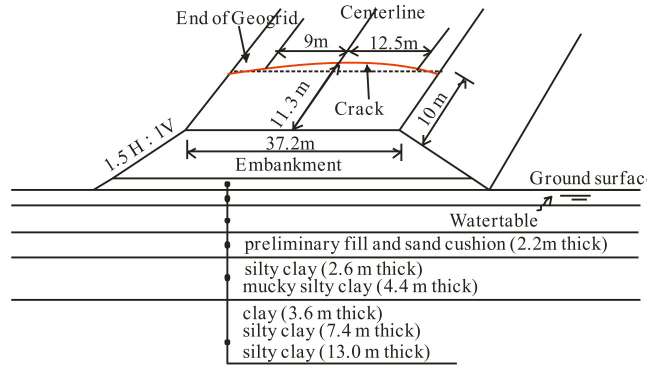

Fig. 2. Detail of the RSW and the ground condition.

2.3. In situ measurement

Below instruments were installed along the centerline of the embankment as shown in Fig. 3:

1) : two settlement plates (C1 and C2) installed at the initial ground surface 4 m and 20 m behind the wall toe to measure the ground settlement;
2) : two sets of magnetic extensometers installed at 2.5 m (S1) and 15 m (S2) away from the wall toe. Five magnets were installed in each extensometer at the depth of 4.4 m, 8.1 m, 11.8 m, 14.6 m and 20.6 m, namely S1-1 to S1-5 and S2-1 to S2-5;
3) : two rows of pore water pressure meters installed at 2 m (P1) and 18 m (P2) away from the wall toe at the depth of 2.6 m, 7 m, 10.6 m, 18 m and 24.5 m, namely P1-1 to P1-6, and P2-1 to P2-6;
4) : four displacement markers on the wall face at the height of 1.7, 2.7, 3.7 and 4.7 m above the toe of the wall to monitor the wall displacement from day 139;
5) : a settlement plate (D1) was installed at 0.5 m away from the wall toe to monitor the displacement of the toe.

3. Measurement results

3.1. Excessive pore water pressure

The measured excess pore water pressures at the monitored depth are shown in Fig. 5. Overall the observed excess pore water pressure in the two rows of pore water pressure meters follows the same trend. The figure shows that at slow loading rate, excess pore water pressure decreased steadily with time, e.g. from day 50–118. Pore water pressure increased rapidly during the days 36–40, 138 to 140, and 187 to 189 when the loading rate was high, especially at shallower depth, e.g. above the depth of −10.6 m. The pore water pressure increment at the deeper locations, e.g. below 18 m, is very low, e.g. less than 10 kPa during the whole period.

There was an unexpected rise of pore water pressure on day 118 in most of the pressure meters, while there were no construction activities. After day 118, the pore water pressure in the ground did not seem to dissipate at all, especially at shallower depth (above −10.6 m). The increase of the pore water pressure observed in the ground on day 118 and slow dissipation of pore water pressure after that is perhaps due to the failure of the PVDs resulting from the large deformation in the ground and wall movement during construction. Chu et al. (2006) found that 200 mm of settlement in a vacuum pressure preloaded PVD drained soft ground can cause the buckling of PVDs and dramatic reduction, e.g. 84%, in the PVD discharge capacity. As shown in Fig. 6 and Fig. 7, till day 118, there was a total settlement of more than 400 mm in C1