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Shear strength of interfaces between unsaturated soils and composite geotextile with polyester yarn reinforcement

Apiniti Jotisankasa[a,*], Natthapat Rurgchaisri[b]

[a] Department of Civil Engineering, Kasetsart University, Jatujak, Bangkok, 10900, Thailand
[b] Italian-Thai Industrial Complex, Wihan Daeng, Saraburi, 18150, Thailand

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A B S T R A C T

Composite geotextiles with polyester yarn reinforcement have been commonly used in combination with unsaturated soils. Both unsaturated and saturated shear strength of the interfaces were investigated between a composite geotextile and three major types of materials: silty sand (SM), low-plasticity silt (ML) and high-plasticity clay (CH) in a direct shear box. The interfaces were formed using two methods (A and B) to reflect the wide range of possible contact conditions in practice. Method A involved statically compacting the soil directly on top of the composite geotextile, while for Method B, the soil was statically compacted in a separate mold and later brought into contact with the composite geotextile. Type B interfaces required a larger displacement to mobilize the shear strength than Type A interfaces. The ultimate failure envelopes of SM and ML soils were similar to those of their interface shearing. Notably, the failure envelopes for the clay-geotextile interface of both types were higher than that of clay alone. The unsaturated soil-only shearing had a higher peak strength and tended to dilate more than saturated soil-only shearing, while unsaturated soil-interface shearing appeared to be more contractant than saturated interface shearing. The strength variations with suction for all tested soils and interface shearing were clearly non-linear. A new model that takes account of the condition of soil-geotextile contact intimacy is proposed for predicting the variation of interface strength with suction, based on the variation of the soil's apparent cohesion with suction and the geotextile-water retention curve.

1. Introduction

An increasingly large number of geosynthetic-reinforced soil (GRS) slopes and embankments have been constructed worldwide since the first development of geosynthetics in the 1970s in Europe and the USA. The technique has spread to Asia and other continents owing to its popularity, simple design, relatively low cost, tolerance to large deformation, and its ease of construction. Traditionally, free draining granular materials are preferred as the backfills of the GRS structures over fine-grained soils (e.g. Elias et al., 2001; AASHTO, 2002). This is due to the granular material's better drainage, higher strength, less volume change, and less tendency of pore-water pressure build up during compaction and rainfall.

However, it might not always be feasible to obtain such free-draining backfills due to scarcity of granular materials on-site, leading to utilization of local materials with large fine contents as backfills. A number of studies (e.g. Murray and Boden, 1979; Tatsuoka and Yamauchi, 1986; Bergado et al., 1993; Zornberg and Mitchell, 1994; Mitchell and Zornberg, 1994; Clancy and Naughton, 2008; Dobie, 2011; Kang et al., 2015) have been conducted to investigate the feasibility of using poorly draining fine-grained soils in reinforced soil structures. Several concerns in using fine-grained backfills include their tendency to develop high pore-water pressure during construction and heavy rainfall, lesser compactability, and higher creep potential. In response to drainage concerns, various types of proprietary permeable reinforcements have been developed to be used in conjunction with fine-grained materials (e.g. Loke et al., 2002; Jeon, 2012; Yoo, 2012; Zornberg and Kang, 2005; Kang et al., 2015). These composite products are normally composed of a non-woven geotextile attached with a certain type of strengthening component (e.g. stitched high strength polyester yarn or geogrid). The non-woven geotextile provides drainage function, while the strengthening component provides additional reinforcement. This better draining quality could help release pore-water pressure build-up in the fill that may occur during construction or in response to water seepage from the retained soil behind the GRS structure. Such composite geotextiles have been promoted as a sustainable technique that enables more efficient use of local materials as well as effective drainage in cases of extreme weathers due to climate

* Corresponding author.
E-mail addresses: fengatj@ku.ac.th (A. Jotisankasa), natthapat.RCS@gmail.com (N. Rurgchaisri).

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change. Some products have also been developed such that they can be incorporated with vegetation to provide ecologically friendly slope greening. Such vegetated geotextile would be placed selectively with materials containing a large proportion of fine contents to enable plant growth (Gray and Sotir, 1996; Goldsmith et al., 2014). Evidently, there are many situations where composite geotextiles are used in combination with various types of backfills.

The strength at interfaces between geotextiles and backfill materials has long been identified as one of the key factors influencing stability of GRS structures and thus has been extensively studied (e.g. Palmeira and Milligan, 1989a; Giroud et al., 1993; Zornberg and Mitchell, 1994; Jones and Dixon, 1998; Liu et al., 2009; Anubhav and Basudhar, 2010; Karademir and David Frost, 2013; Fowmes et al., 2017; Yu and Bathurst, 2017; Punetha et al., 2017; Lal et al., 2017; Afzali-Nejad et al., 2017). In fact, backfill materials are nearly always placed in the GRS structure in the unsaturated condition and would have some apparent cohesions due to the soils' matric suctions. The matric suction, $s = (u_a - u_w)$, is defined as the difference between pore-air pressure, u_a, and pore-water pressure, u_w. Rainfall infiltration and seepage would increase the saturation condition of the fill, reducing the soil's suction and its strength (e.g. Vahedifard et al., 2016). A number of studies have been conducted to investigate the performance of various geotextiles and geocomposites in unsaturated reinforced earth structures (e.g. Iryo and Rowe, 2005; Bouazza et al., 2006; Tolooiyan et al., 2009; Portelinha and Zornberg, 2017; Chinkulkijniwat et al., 2017). It has been demonstrated that non-woven geotextiles as well as composite geotextile layers could act as a barrier to unsaturated seepage due to their relatively low permeability in a negative pore pressure range, while being an effective drainage in the saturated case. Iryo and Rowe (2005) suggested that the role of non-woven geotextile layers as a drainage material was of lesser importance on GRS stability than their role as a reinforcing material. Bouazza et al. (2006) and Portelinha and Zornberg (2017) stated that an unsaturated geosynthetic drainage layer could provide an increase in moisture storage through the depth of a soil profile, thus performing as capillary break. Recent reports (e.g. Simpson and Tatsuoka, 2008; Fowze et al., 2012; Yoo, 2012; Liu et al., 2012; Bergado et al., 2014) indicated that more extreme heavy rainfall due to climate change would make reinforced slopes and embankments more susceptible to failure or excessive deformation due to infiltration. These studies highlight the needs for studying soil-geotextile interfaces in unsaturated condition.

Recognizing the importance of suction on interface strength, a number of researchers (e.g. Fleming et al., 2006; Khoury et al., 2011; Esmaili et al., 2014; Huang et al., 2017) have investigated the unsaturated interface strength in the direct shear box and the pullout apparatus. It was demonstrated that the rate of increase in interface strength with suction was non-linear and could be substantially lower than that of the soil-only shearing. The soil-water retention curve and the extended Mohr-Coulomb theory have been used to explain this phenomenon. These studies are however limited to plain geotextile or geomembrane and a few type of soils. More research is still needed on the unsaturated strength of interfaces between composite geotextiles and a variety of locally sourced soils, given their increasing use in practice. This paper reports on both unsaturated and saturated shear strength of interface between a composite geotextile and three majors types of materials: silty sand, low-plasticity silt and high-plasticity clay, in a direct shear box. A new predictive model for unsaturated soil-geotextile interface strength, based on soil strength and geotextile-water retention curve, is proposed.

2. Testing methods and materials

2.1. Apparatus

Both soil shear strength and interface strength between the soil and the composite geotextile were tested in a direct shear box. The conventional slow direct shear tests following ASTM D3080/D3080M-11 (2011) were conducted to determine saturated effective strength parameters. Saturated interface shear strength was tested in the direct shear box using a procedure similar to those by Anubhav and Basudhar (2010) and Khoury et al. (2011). The sizes of direct shear boxes used in their studies and in the current study were about 63 mm in diameter. However, a number of previous studies on soil-geotextile interface and reinforced soils, as well as ASTM D5321, employed a direct shear box of about 300 mm in size or larger (e.g. Palmeira and Milligan, 1989a; Hsieh and Hsieh, 2003; Liu et al., 2009). Many past researchers (e.g. Palmeira and Milligan, 1989b; Cerato and Lutenegger, 2006; Wu et al., 2007; Dadkhah et al., 2010; Ziaie moayed et al., 2016) investigated the size effect of the direct shear box on soil strength, indicating that a smaller shear box (60 mm) can result in a higher strength than that from a 300 mm shear box in peak condition, while giving nearly the same residual strength. Ziaie moayed et al. (2016) found that the apparent cohesion in sandy soils could range from 7 to 20 kPa in a 60 mm shear box, while being close to zero in a 300 mm shear box. In summary, the size effect of the shear box on the measured strength can be attributed to factors such as varying shear zone thickness, non-uniformity of stress-strain, progressive failure, boundary mechanical restraint and shear band, which are dependent on soil type, fine content and initial density. Nevertheless, 60 mm shear boxes have been used to obtain valuable information on interface behavior; for example, unsaturated interface behavior (Khoury et al., 2011) and post-peak behavior (Anubhav and Basudhar, 2010). Based on studies by Jotisankasa and Taworn (2016, 2016), the rate of increase in strength with suction appeared to be unaffected by specimen size. Therefore, it was assumed in the current study that any increase in soil strength due to the smaller shear area was the same for all suctions, and the interpretation of any additional strength due to suction of the unsaturated soils and interfaces could be done without adverse effects resulting from the smaller shear area.

For unsaturated samples in the current study, the suction-monitored direct shear tests as explained by Jotisankasa and Mairaing (2010) were carried out to determine the shear strength variation with suction in a constant water content (CW) condition. In the CW situation, pore-air pressure, u_a, is constant, being equal to atmospheric value, while the pore-water pressure, u_w, can change in response to changes in soil structure during shearing. This technique was modified for testing the unsaturated interface strength in the current study as shown in Fig. 1. Notably, the matric suction was measured on the top surface of the sample because it was impracticable to attach the tensiometer at the mid-height of shear box side due to the limitation in height of the shear box. There was uncertainty regarding the equilibration of suction throughout the sample due to non-uniformities of strain and boundary conditions during shearing. Studies using suction-monitored triaxial tests (Jotisankasa et al., 2009a) and suction-monitored large direct shear tests (Jotisankasa and Taworn, 2016) suggested that for various conditions, the differences between suctions monitored at different parts of samples could be in a range of 10–20% during shearing. Major benefits of the CW test are its relatively short test duration and the relative simplicity of the required equipment, whilst still yielding results similar to the constant suction tests (e.g. Toll and Ong, 2003; Jotisankasa et al., 2009a). The CW test would also realistically represent a field loading condition where the water content remains unchanged.

In the current study, soil suction was either measured directly throughout the test using a miniature tensiometer inserted through an orifice in a top cap (for suction < 100 kPa) or estimated from the soil-water retention curve (for suction > 100 kPa). Due to the presence of vented gap around the sample shear plane between the two halves of shear box, the pore-air pressure, u_a, were assumed zero. To maintain a constant water content during testing, a plastic wrapping and wet cloths were used to cover the shear box to prevent sample's evaporation. The CW condition was ensured by checking soil moisture content before and