Geotextiles and Geomembranes xxx (2017) 1–9

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

journal homepage: www.elsevier.com/locate/geotexmem

Technical note

Model geogrids and 3D printing

Dionysios Stathas [a], J.P. Wang [a, b, *], Hoe I. Ling [c]

[a] Department of Civil & Environmental Engineering, Hong Kong University of Science and Technology, Kowloon, Hong Kong
[b] Department of Civil Engineering, National Central University, Zhongli, Taiwan
[c] Department of Civil Engineering & Engineering Mechanics, Columbia University, 500 West 120th Street, New York, NY 10027, United States

ARTICLE INFO

Article history:
Received 7 June 2016
Received in revised form
5 June 2017
Accepted 2 July 2017
Available online xxx

Keywords:
Geosynthetics
3D printing
Geogrid
Tensile strength
Aperture size

ABSTRACT

This paper summarizes the technical aspects of using 3D printing to fabricate small model geogrids for geotechnical experiments, with the aim of scaling their geometry and tensile behavior under operational conditions, say up to 5% strain. Specifically, we successfully fabricated model geogrids with one-hundredth of the tensile strength of prototypes, which is desirable for 1:10 model tests under 1-g condition. We also successfully fabricated another one with tensile strength close to one-tenth of prototypes, which is desirable for 1:10 model tests under 10-g condition in centrifuges. Therefore, by using 3D-printed model geogrids with properly scaled dimensions and tensile behavior, it is possible to achieve the two scaling laws simultaneously in reinforced-soil model tests, making the small-scale model tests more representative of field conditions.

1. Introduction

Geogrids and other geosynthetics are widely used in geotechnical engineering. For example, it is common today to install geogrids in the backfill of soil-retaining walls to improve the system's performance (e.g., Allen and Bathurst, 2014a, 2014b; Balakrishnan and Viswanadham, 2016; Koerner, 2012; Leshchinsky et al., 2014; Ling et al., 2009; Shukla, 2012; Xie and Leshchinsky, 2015). Installing geogrids in soil creates a composite material with improved mechanical properties given that the tensile strength of soil is inherently low.

A common approach adopted in geotechnical research is based on model test results. However, due to the cost and difficulties associated with model preparation, full-scale model tests/studies are rare compared to small-scale tests, although they are usually more representative of field conditions and reliable (e.g., Bathurst et al., 2006, 2009; Ling et al., 2012). Under these circumstances, it is important to use proper scaling laws in small-scale geotechnical tests. For example, according to Madabhushi (2015), the amount of time required for soil consolidation must be scaled by a factor of n^2 when small-scale models are subjected to n-g condition in centrifuges. Similarly, the properties of geogrids (such as dimensions and tensile strength) used in model tests must be scaled accordingly (Garnier et al., 2007; Springman et al., 1992; Viswanadham and König, 2004). For instance, the tensile strength of model geogrids used in 1:N reinforced-soil models must be $1/N^2$ of that of full-scale geogrids when the test is carried out under 1-g condition, or n/N^2 of that of prototype (geogrids) under n-g condition in centrifuges (Viswanadham and König, 2004). Note that N represents the scale of a reduced model (e.g., 1:10), and n is the level of gravity (e.g., 10 g) that the model is subjected to; usually, n is equal to N.

Geosynthetic reinforcement, however, is not easy to scale in small-scale model tests (e.g., El Sawwaf, 2006; Moghaddas-Nejad and Small, 1996; Wang et al., 2015; Xiao et al., 2016; Yoo, 2001). For example, Chen and Chiu (2008) used paper as reinforcement in 1-g experiments but the material's tensile strength/stiffness was unknown. Tatsuoka et al. (1989) and Koseki et al. (1998, 2003) fabricated model geogrids out of phosphor-bronze strips for their small-scale tests to study the dynamic response of retaining walls. The material was strictly elastic, but the stress-strain curve was not available. Thus, it is difficult to assess if the scaling laws for tensile strength were properly matched in their study. On the other hand, instead of using model geogrids, Patra et al. (2006) used full-scale geogrids in their small-scale tests (i.e., 80 × 360 mm) to investigate the stability of a foundation under eccentric loading, which might not be appropriate with the scaling laws not considered.

---

* Corresponding author. Department of Civil Engineering, National Central University, Zhongli, Taiwan.
E-mail address: jpwang@ust.hk (J.P. Wang).

http://dx.doi.org/10.1016/j.geotexmem.2017.07.006
0266-1144/© 2017 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Stathas, D., et al., Model geogrids and 3D printing, Geotextiles and Geomembranes (2017), http://dx.doi.org/10.1016/j.geotexmem.2017.07.006

Some studies did provide mechanical data for model geogrids used in their tests. For instance, Ling et al. (2004) tested their fiberglass model geogrids with a tensile strength of 8.6 kN/m and used them in 50-g centrifuge tests to investigate the dynamic behavior of geosynthetic-reinforced retaining walls; based on scaling laws, the tensile strength of their model geogrids would have been 430 kN/m (= 8.6 × 50) in prototypes, which is approximately three to four times larger than most full-scale geogrids available on the market (e.g. BBA, 2013). Similarly, Lee et al. (2010) used model geogrids with a tensile strength of 27.7 kN/m in their 10-g centrifuge tests, which would have resulted in a tensile strength of 277 kN/m (= 27.7 × 10) in prototypes, closer to the tensile strength of full-scale geogrids ranging from 50 to 150 kN/m. The study highlighted the importance of stiffness scaling for the model reinforcement used in a reinforced-soil study. Likewise, the K-stiffness method (Allen et al., 2003; Bathurst et al., 2008) and the improved simplified method (Allen and Bathurst, 2015) were both proposed to take into account the fact that reinforcement stiffness plays a more critical role than ultimate strength in the serviceability of geosynthetic-reinforced structures. Therefore, the reinforcement material used in small-scale model tests must have a tensile strength/stiffness close to prototypes if the test results are to be representative. The series of centrifuge studies conducted by Ling et al. (2016) also confirmed that modeling of stiffness is more relevant compared to strength of geogrid.

In addition to tensile stiffness (or the stress-strain relationship), the geometry (e.g., the aperture of geogrids) must also be properly scaled for a more accurate modeling of the soil-geogrid interface in reinforced-soil model tests (Springman et al., 1992). The task is relatively easy for biaxial geogrids, since everyday items such as mosquito nets can be used owing to their similar geometries (e.g., Viswanadham and Jessberger, 2005). However, the task becomes challenging for uniaxial geogrids due to their unique texture/appearance. Therefore, few geotechnical studies used properly-scaled uniaxial geogrids in their small-scale experiments, and those that did rely on small, custom-made uniaxial geogrids that were directly ordered from geogrid manufacturers (Sharma and Bolton, 1996; Springman et al., 1992).

3D printing has become a revolutionary technology since its emergence in the mid-1980s (Berman, 2012; Choxi, 2016). It is an additive manufacturing process, in contrast to conventional techniques (e.g., using Computer Numerical Control machines) which cut the desired object out of a bigger one. Currently, several 3D printing techniques are available such as photopolymerization, extrusion, and lamination, and the selection of technique usually depends on the desired object. The past few years have seen many innovative applications of 3D printing, including successful attempts to create medical implants (Murphy and Atala, 2014). In civil engineering, a project aiming to build a bridge using 3D printing is expected to be completed sometime in 2017 (Cooper, 2015).

Recently, 3D printing has also been adopted in geotechnical research. For instance, Miskin and Jaeger (2013) successfully reproduced the structures of different granular materials using 3D printers and tested their stress-strain relationship as a benchmark for numerical simulations. Similarly, Hanaor et al. (2016) and Matsumura et al. (2015) investigated the behavior of soil by conducting triaxial tests on 3D-printed particles.

Other geotechnical projects using 3D printing include those of Jiang et al. (2016), Shen et al. (2016), Stathas and Wang (2015) and Yuan et al. (2016). Specifically, Jiang et al. (2016) manufactured moulds and replicated the structure of natural rock joints using 3D printers. Stathas and Wang (2015) 3D-printed small gabion and modular-block retaining walls for a performance comparison with small-scale model tests. On the other hand, Yuan et al. (2016) developed a novel biaxial testing system to study soil interactions with its key components fabricated using 3D printers.

Using 3D printing, the current study aims to prepare model geogrids with properly scaled geometry and tensile behavior for small-scale laboratory tests, given that past attempts have not been satisfactory. Specifically, we successfully fabricated a uniaxial model geogrid with its stress-strain relationship and stiffness scaled to one-hundredth of those of full-scale geogrids, which is desirable for 1:10 reinforced-soil model tests under 1-g condition (Viswanadham and König, 2004). At the same time, the geometry of the model geogrids – uniaxial or biaxial – can be easily achieved with 3D printing, providing a more accurate modeling of the soil-geogrid interface, which is important for physically modeling with respect to reinforced-soil structures.

2. 3D printer

This study used the Connex350 3D printer from Stratasys, available in the Design and Manufacturing Facility of the Hong Kong University of Science and Technology. Unlike other basic models, Connex350 fabricates an object by mixing different materials via photopolymerization processes. The object's mechanical properties can thus be adjusted, so that it can be made very stiff or very flexible depending on the design requirements.

Connex350 uses base resins to produce *Digital Materials* for 3D printing. The base resins are photopolymers that solidify upon exposure to UV radiation. Currently, around 10 different base resins, such as *Verowhiteplus*, *Tangoblackplus*, and *Endur* (or *Rigur*), have been used in 3D printing. Summarized in Table 1, the tensile strength of *Verowhiteplus*, for example, is approximately 58 MPa, while it is only 0.8–1.5 MPa for *Tangoblackplus*. As mentioned previously, the mechanical properties of 3D-printed objects can be controlled by mixing the materials during the printing process. However, currently only around 10 material combinations are provided by Stratasys. Specifically, a *Digital Material* called *RGD8530* that has a tensile strength of 29–38 MPa consists of *Verowhiteplus* as the primary material and *Tangoblackplus* as the secondary. Stratasys recommends printing polypropylene-based objects using *RGD8530* or *Endur* as *Digital Materials*, considering their similar mechanical properties at the material level.

In this study, *RGD8530* and *Verowhiteplus* were used to prepare the model geogrids given that the mechanical properties are similar to full-scale geogrids. A model geogrid made of *Tangoblackplus* at specified scaling would not be up to the task owing to its very low strength and high elongation at break. *Endur* was also used in this study to test the influences of printing direction and sample size on the tensile strength of the model geogrids.

3. Model geogrids and testing

3.1. 3D-printed model geogrids

The model geogrids that were designed and tested in this study were on a scale of 1:10 so that we could investigate the behavior of geosynthetic-reinforced soil structures with a 1:10 models in the follow-up studies. Nevertheless, the technical aspects of using 3D printing to fabricate model geogrids presented here can be applied to similar projects with a different factor than 1:10.

The first step in 3D printing is to design the object with a CAD software, such as 123Design from Autodesk. Fig. 1 shows our designs with the software based on full-scale geogrids (i.e., Tensar 55RE and E'GRID4040 of BOSTD). As shown in the figure, the 3D-printed model geogrids closely resemble the full-scale ones in terms of both appearance and dimensions, and it took approximately 30 min to print the object in dimension 6 × 15 cm.

In total, nine different uniaxial and biaxial (model) geogrids are

Please cite this article in press as: Stathas, D., et al., Model geogrids and 3D printing, Geotextiles and Geomembranes (2017), http://dx.doi.org/10.1016/j.geotexmem.2017.07.006