Investigation of global stress-strain and interaction behavior of geogrid reinforced soil with biaxial compression tests

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ABSTRACT

After decades of application of the modern composite material geogrid reinforced soil, its design can still be improved. With the development of increasingly strong techniques of numerical modeling (finite element or finite difference methods), attention is refocusing on correct modeling of the complex interaction behavior between the two materials as its description with common interface models has been unsatisfactory so far. A sophisticated large-scale biaxial compression test device at RWTH Aachen University with a transparent side wall has been developed, allowing the quantitative investigation of the soil-geogrid interaction mechanisms. In this study, a special test series of specimens, reinforced with geogrid samples with different numbers of longitudinal and transverse tensile members, is used to quantify the effects of the load transfer mechanisms on the global stress-strain behavior. Additionally, an interaction model, recently developed for pullout situations that explicitly takes into account the separate load transfer mechanisms, is transferred to the plane strain conditions of biaxial compression tests. First results, presented in this paper, are promising and show that the model is capable of describing the complex interaction between geogrid and soil.

Keywords: Geogrid reinforced soil, biaxial compression testing, stress-strain behavior, interaction/load transfer behavior, interaction model, interface

1 INTRODUCTION

After decades of successful application of geogrid reinforced soil as modern composite material, design concepts can still be improved as they, due to the lack of mechanically sound models, often base on empirical studies. Furthermore, with increasing use of advanced numerical modeling (finite element or finite difference methods) for design and for the generation of synthetic data, attention is refocusing on correct modeling of the complex interaction between geogrid and soil. The description of the interaction, i.e. the load transfer, has been the weak point so far, being characterized insufficiently with common interface models and elements.

To investigate the compound stress-strain behavior and the load transfer between geogrid and soil, large-scale biaxial compression tests have been carried out with geogrid reinforced soil at RWTH Aachen University. In the tests, large specimen dimensions (H x W x D = 80 x 81 x 46 cm³) have been used to profit from a non-scaled ratio between geogrid aperture and soil grain size. With its plane strain condition, the biaxial compression test reproduces the state of strain of many geogrid reinforced soil applications and due to its highly defined boundaries it is similar to an “element” test. According to Ketchart & Wu (2001), the biaxial compression test is therefore the most appropriate testing methodology for geogrid reinforced soil.

For the investigation of the interaction behavior, as Bathurst (2014) just stated recently, it is necessary “to provide quantitative insight into soil-geogrid interaction mechanisms”, which Ezzein & Bathurst (2011, 2014) and Ferreira & Zornberg (2014) do by using transparent granular soil in pullout boxes with transparent bottom. In the biaxial compression tests developed by Ruiken (2013) at RWTH Aachen University, the interaction mechanisms can be studied directly as well; the side wall of the biaxial device is transparent, allowing to observe the entire specimen cross-section during the test. Using sequential photographs, the soil deformation is evaluated with the Digital Image Correlation (DIC) method.
While the geogrid is loaded directly in pullout tests, in the presented biaxial compression test, as in most applications of geogrid reinforced soil, the load is applied to the soil, leading to an indirect loading of the reinforcement via the soil.

In both conditions, geogrid reinforced soil works due to the load transfer from soil to geogrid, and vice versa. The commonly known working mechanisms are friction and bearing resistance due to relative displacement perpendicular to any tensile members. Those interaction mechanisms have been investigated in many studies (e.g. Jewell et al., 1984; Ochiai et al., 1996; Lopes, 2002; Palmeira, 2004; Ziegler & Timmers, 2004; Sieira et al., 2009; Müller, 2011, 2014), mostly with pullout tests.

With the developed device, the effects of the two interaction mechanisms were shown in detail in previous publications (Jacobs, 2013 and Jacobs et al., 2013) by the global stress-strain behavior and shear zone developments. In this paper, the two interaction mechanisms will be additionally modeled explicitly with an interaction model (see Müller, 2011 & 2014 and Jacobs et al., 2014) adapted for the prevailing test boundary conditions.

2 EXPERIMENTAL INVESTIGATION OF LOAD TRANSFER WITH BIAXIAL COMPRESSION TESTS

2.1 Test setup and materials

The laboratory apparatus that has been developed by Ruiken (2013) to carry out large scale biaxial compression tests with geogrid reinforced soil is shown in Fig. 1. In this paper, test results of unreinforced specimens and specimens reinforced with two reinforcement layers are presented (two layers were found to be the most appropriate, see Ruiken et al., 2012). Tests have been carried out under a constant confining pressure of \( \sigma_3 = 2.5 \text{kPa} \) that was applied using vacuum, representing the horizontal in situ stress of shallow bearing layers. Axial compression of the soil has been achieved with a stiff loading plate that has been moved with constant velocity \( \approx 1 \text{ mm/min} \). Due to the low confining stress, loading with an air pressure cushion is not possible. However, the resulting non-uniform pressure distribution between the stiff loading plate and the top surface of the specimen has been measured with a sensitive high resolution pressure sensor.

The presented tests have all been carried out with dry uniform-graded medium sand \( (d_{50} = 0.5 \text{ mm}; d_{90} = 1.7 \text{ mm}) \), classified as “SP” according to the Unified Soil Classification System (ASTM D2487). Each specimen was prepared using a rainfall technique so that a high relative density of \( R_D = 89 \% \) has been reached (density \( D = 1.74 \text{ t/m}^3 \), see Ruiken et al., 2010).

In this paper, results of a test series are presented, where the geogrid samples had been modified from original BIAXIAL geogrids (polypropylene grids with flat bars and welded junctions, tensile strength of 30 kN/m and tensile stiffness of \( J_{0.2} = 700 \text{ kN/m} \)). STRIP reinforcement was created by carefully removing all transverse members, and UNIAXIAL reinforcement by removing every second transverse member. Note that thereby, the tensile strength and stiffness of the reinforcements in longitudinal direction were the same for all reinforced samples.

2.2 Test results

The stress-strain curves of the regarded biaxial compression tests are presented in Fig. 2. The unreinforced and reinforced tests show the typical behavior of dense sand with a peak strength and decay to the residual strength. Adding only longitudinal geogrid members as STRIP reinforcement to the
specimen, leads to an increase in ultimate strength (> 150 %) and in stiffness. However, real geogrids including transverse members within the samples exceed the reached ultimate strength and stiffness easily. The test sample with regular biaxial reinforcement shows an ultimate strength of 216 kPa, of which approx. 20 % is caused by the unreinforced soil itself, approx. 40 % by the frictional and approx. another 40 % by the bearing load transfer.

With that, these two load transfer mechanism have been shown and their effects on the global stress-strain behavior quantified. For details on the effects of the load transfer mechanisms on the kinematic behavior, see Jacobs (2013).

3 EXPLICIT MODELLING OF LOAD TRANSFER

3.1 Interaction mechanisms and model development under pullout loads

Many researchers have studied the interaction mechanisms of geogrids with soil using pullout tests (e.g. Jewell et al., 1984; Ochiai et al., 1996; Lopes, 2002; Palmeira, 2004; Ziegler & Timmers, 2004; Sieira et al., 2009; Müller, 2011, 2014) and all agree that there are two basic mechanisms:
- Friction, mainly on the longitudinal tensile members,
- Bearing, a passive earth pressure developing in front of the transverse tensile members.

Ziegler & Timmers (2004) put forward a simple model to describe this displacement-dependent bearing in front of the transverse members as passive earth resistance against the movement of a tensile member transverse to the soil (see Fig. 3). It is known that with increasing relative displacement between the two materials the mobilized area of this passive resistance also increases and the bearing resistance in front of one transverse member \( T_{\text{mobil}} \) is assumed to be the integrated shear stress \( \tau_S \) on top and bottom of the mobilized soil area:

\[
T_{\text{mobil}} = 2 \int \tau_S \, dA \cdot n_g = 2 \int \sigma_n \cdot \tan \phi_S \, dA \cdot n_g
\]

\[
= 2 \cdot \sigma_n \cdot \tan \phi_S \cdot a_i \cdot \text{mob} L(u_{\text{mobil}}) \cdot n_g
\]  

where \( A \) = mobilized area of passive earth resistance, \( n_g \) = number of longitudinal tensile members per unit width, \( \sigma_n \) = normal pressure in geogrid members, \( \phi_S \) = internal friction angle of the soil, \( a_i \) = aperture width between two longitudinal tensile members as shown in Fig. 3, and \( \text{mob} L(u_{\text{mobil}}) \) = mobilized length of passive earth resistance, depending on the transverse tensile member displacement \( u_{\text{mobil}} \).

Müller (2011, 2014) used and verified the above proposed model to simulate a fictional pullout test, where the plane geogrid is modeled in one dimension and is divided into a finite number of longitudinal elements. These elements are either pure frictional longitudinal elements or frictional longitudinal elements with a connected transverse tensile member so that the mobilized earth pressure is transferred to the longitudinal element at this point. The tensile load (per unit width) \( T_i \) and the displacement \( u_{g,i} \) at one end of each element as shown in Fig. 4 are calculated by:

\[
T_{i+1} = T_i - 2 \cdot \Delta L \cdot W_i \cdot \sigma_n \cdot \tan \left( \delta(u_{g,i+1}) \right) \cdot n_g
\]

\[
- T_{\text{mobil},i+1} \left( u_{g,i+1} \right)
\]

\[
u_{g,i+1} = u_{g,i} + \varepsilon(T_i) \cdot \Delta L
\]

where \( \Delta L \) = element length, \( W_i \) = width of longitudinal tensile member, \( \delta(u_{g,i+1}) \) = mobilized true friction angle between longitudinal geogrid member and soil, \( u_{g,i} \) = relative displacement between geogrid and soil, and \( \varepsilon(T_i) \) = force-strain relation of geogrid.

For pullout conditions, the assumption of no movement of soil parallel to the geogrid is valid so that the relative displacement between geogrid and soil \( u_g \) is equal to the geogrid displacement \( u_g \). For other conditions:
\[ u_{sg,i+1} = u_{sg,i} - u_{g,i} \]  
(4)

where \( u_{i,j} \) = displacement of soil surrounding element \( i \).

For this interaction model, the following three material/material-soil property functions are necessary as input:

1. Force-strain relation of the geogrid \( c(T) \) (in machine direction), including tensile strength. Depending on the geogrid polymeric material and its production process this function needs to take into account creep and strain rate effects (e.g. Thornton, 2001; Ezzein et al., 2014; Kongkitkul et al., 2014).

2. Mobilized true friction angle between longitudinal tensile member and soil \( \delta(u_{sg}) \). This depends on the stress level and the soil density, and is obtained with geogrid samples without any transverse tensile members.

3. Mobilized length of activated bearing resistance area in front of transverse tensile members \( mob L(u_{cmd}) \). It is approximately independent of the stress level, but is highly influenced by soil density. This function is achieved by comparison of tests with geogrid samples with 1 and with 0 transverse members. Additionally, it needs to include a failure criterion for the junction strength.

See Jacobs et al. (2014) for more details on these input functions.

Jacobs et al. (2014) carried out more than 120 pullout tests in a regularly sized test box to evaluate and to calibrate the necessary input functions for the interaction model. Furthermore, they validated the model with pullout tests in a large-scale test box and measurement data from an in situ anchorage trench on top of a geogrid reinforced slope. To use this interaction model in a biaxial compression test with different boundary conditions than those of a pullout test, some adaptations are necessary, which are described in the next chapter.

3.2 Adaption of model to biaxial compression test conditions and first model results

The advantage of investigating geogrid reinforced soil with biaxial compression tests lies in the plane strain condition and in the fact that the geogrid is activated via the soil, both conditions being relevant for most applications but differing from pullout conditions. However, the authors believe that the main interaction mechanisms, i.e. frictional and bearing components, act similarly as in pullout tests. Therefore, the developed pullout interaction model can easily be transferred to describe the interaction within a biaxial compression test, taking into account the different boundary conditions.

In contrast to pullout test conditions, here the normal pressure on the geogrids \( \sigma_n \) is neither constant in space nor time (the latter being expressed by global compressions state \( \varepsilon_L \)), and the soil can deform freely in one horizontal direction. Fig. 5 (top left) shows the prescribed boundary stress \( \sigma_m \), the measured boundary stress \( \sigma_{m,op} \) and the horizontal soil displacement \( u_h \) for the global compression state of \( \varepsilon_L = 1 \% \). Those are used to evaluate the input functions of normal pressure and soil displacement in the geogrid planes, illustrated in Fig. 5 in the top right part (graph a and b) for half of a specimen (symmetry assumed).

Starting from the symmetry boundary with a maximum tensile geogrid force value, integration along the geogrid and solving Eq. (2) to (4) leads to the distributions of geogrid strain, geogrid tensile force, geogrid deformation and relative displacement between geogrid and soil. Iteratively varying the maximum geogrid tensile force, a valid solution is found when the geogrid force is zero at the free end of the geogrid. This is shown exemplarily at the bottom of Fig. 5 (graphs c to f) with dotted lines for the modeling of a test reinforced with geogrids without any transverse tensile members (only frictional load transfer acting). For calibration of the model, the modeled geogrid strain distribution, drawn as dotted line in Fig. 5, graph c, can be compared with the measured strain distribution (solid line).
4 CONCLUSIONS

Large-scale biaxial compression tests were carried out at RWTH Aachen University investigating the compound stress-strain behavior of geogrid-reinforced soil and the interaction behavior of its two components. In detail, the following conclusions are drawn:

- The impact of the two load transfer mechanisms, i.e. friction and bearing caused by geogrid transverse tensile members, on the global stress-strain behavior was quantified with a special test series involving modified geogrid samples. For a specimen reinforced with a regular biaxial geogrid, the unreinforced soil caused approx. 20% of the total bearing capacity, the frictional load transfer approx. 40% and the bearing load transfer approx. another 40%.

- An interaction model, recently developed for pullout situations, explicitly modeling both load transfer mechanisms, was adapted for plane strain conditions with loading of the geogrids via the soil.

- First results showed that this model is capable of describing the interaction between soil and geogrid.

In a next step, the developed model will be calibrated using the data of the special test series involving geogrid samples with various numbers of longitudinal and transverse members, i.e. different tensile stiffnesses and aperture sizes, respectively. With this step, the validity of the assumed bearing model by Ziegler & Timmers (2004) also for conditions as in the biaxial compression test will be shown. Once calibrated, it can be used to evaluate shear stress input functions for an enhanced interface between geogrid and soil to improve finite element modeling of geogrid reinforced soil.

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REFERENCES

1) Bathurst, R.J. (2014): Challenges and recent progress in the analysis, design and modelling of geosynthetic reinforced soil walls, Proceedings of the 10th International Conference on Geosynthetics - Giroud Lecture, Berlin, Germany.

2) Ezzein, F.M. and Bathurst, R.J. (2011): A transparent sand for geotechnical laboratory modeling, ASTM Geotechnical Testing Journal, 34(6), 590-601.

3) Ezzein, F.M. and Bathurst, R.J. (2014): A new approach to evaluate soil-geosynthetic interaction using a novel pullout test apparatus and transparent granular soil, Geotextiles and Geomembranes, 42(3), 246-255.

4) Ezzein, F.M., Bathurst, R.J., and Kongkitkul, W. (2014): Non-linear load-strain modelling of polypropylene geogrids during constant rate-of-strain loading, Polymer Engineering and Science, DOI: 10.1002/pen.23999.

5) Ferreira, J.A.Z. and Zornberg, J.G (2014): Behavior of Transverse Ribs in a Tensioned Geogrid
Embedded in Transparent Soil,  Proceedings of the 10th International Conference on Geosynthetics, Berlin, Germany.

6) Jacobs, F. (2013): Investigation of Geogrid Reinforced Soil Using Biaxial Compression Tests,  Proceedings of the 5th International Young Geotechnical Engineers’ Conference : 5th iYGEC, Paris, France. ISBN: 978-1-61499-296-7, 978-1-61499-297-4, 318-321.

7) Jacobs, F., Ziegler, M., and Ruiken, A. (2013): Experimental Investigation of the Stress-Strain Behaviour of Geogrid Reinforced Soil,  Proceedings of 2nd African Regional Conference on Geosynthetics, Accra, Ghana, ISBN 978-0-9884772-1-6 (CD).

8) Jacobs, F., Ziegler, M., Vollmert, L. and Ehrenberg, H. (2014): Explicit Design of Geogrids with a Nonlinear Interface Model,  Proceedings of the 10th International Conference on Geosynthetics, Berlin, Germany.

9) Jewell, R.A., Milligan, G.W.E, Sarsby, R.W. and Dubois, D. (1984): Interaction between soil and geogrids,  Symposium on Polymer Grid Reinforcement in Civil Engineering ‘84, ICE, London, UK, 18-30.

10) Ketchart, K. and Wu, J.T.H. (2001): Performance test for geosynthetic-reinforced soil including effects of preloading. U.S. Department of Transportation – Federal Highway Administration. Report No. FHWA-RD-01-018.

11) Kongkitkul, W., Chantachot, T. and Tatsuoka, F. (2014): Simulation of geosynthetic load-strain-time behaviour by the non-linear three-component model,  Geosynthetics International, 21(4): 244-255.

12) Lopes, M.L. 2002: Soil-geosynthetic interaction. Geosynthetics and their applications, Ed. Shukla, S.K., Thomas Telford.

13) Müller, W. (2011): Zur Bemessung der Verankerung von Bewehrungsgittern aus Kunststoff beim Schutz von Böschungen vor hangparallellem Gleiten,  Bautechnik, 88(6): 347-361, language: German.

14) Müller, W. (2014): Long-term pull-out resistance and material properties of geogrids,  Proceedings of the 10th International Conference on Geosynthetics, Berlin, Germany.

15) Ochiai, H., Otani, J., Hayashi, S. and Hirai, T. (1996): The pull-out resistance of geogrids in reinforced soil.  Geotextiles and Geomembranes, 14(1): 19-42.

16) Palmeira, E.M. (2004): Bearing force mobilisation in pull-out tests on geogrids,  Geotextiles and Geomembranes, 22(6): 481-509.

17) Ruiken, A., 2013. Zum Spannungs-Dehnungsverhalten des Verbundbaustoffs „geogitterbewehrter Boden“. Ph.D. Thesis, RWTH Aachen University, Germany, language: German.

18) Ruiken, A., Jacobs, F. and Ziegler, M. (2012): Large scale biaxial compression testing of geogrid reinforced soil.  Proceedings of 5th European Geosynthetics Congress, Valencia, Spain, 4: 301-306.

19) Ruiken, A., Ziegler, M., Ehrenberg, H. and Höhny, S. (2010): Determination of the soil confining effect of geogrids.  Proceedings of 14th Danube-European Conference on Geotechnical Engineering, Bratislava, Slovak Republic, 1-4.

20) Thornton, J.S. (2001): Characterization of Short and Long Term Creep and Relaxation Properties of a Polypropylene Geogrid,  Geosynthetics, 835-845.

21) Sieira, A.C.C.F., Gerscovich, D.M.S. and Sayão, A.S.F.J. (2009), Displacement and load transfer mechanisms of geogrids under pullout condition,  Geotextiles and Geomembranes, 27: 241-253.

22) Ziegler, M. and Timmers, V. (2004). A new approach to design geogrid reinforcement,  Proc. of the 3rd European Geosynthetics Conf., Geotechnical Engineering with Geosynthetics 2004, 661-666.