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Interaction behaviour of geogrids in transparent soil

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ABSTRACT: The interaction behaviour of geogrid-reinforced soil is significantly influenced by the direction of force transmission between geogrid and soil. If a geogrid is pulled out of the soil, the geogrid force is anchored in the surrounding soil. In contrast to that, an applied load via the surrounding soil activates geogrids in base layers. For example, in case of a base reinforced embankment, the soil is pushed over the geogrid at the edges of the load area, whereby the spreading forces are transferred into the geogrid. The interlocking mechanism occurs in the core area of the embankment, if there is no relative movement between soil and geogrid. The geogrid activation caused by a load via the surrounding soil involves a fundamental need for research. This paper gives an overview of the existing concepts of interaction and classifies them into macro- and micro-scale as well as different kind of geogrid activation.

Tests with reinforced transparent specimens are presented as an investigation method for an area-wide and undisturbed measurement of geogrid and soil deformations using the digital image correlation method. The transparent soil is created as a two-phase medium consisting of crushed fused quartz and white oil with a corresponding refractive index.

1 INTRODUCTION

In geotechnical practice, the composite material geogrid-reinforced soil has a wide range of applications (Ziegler 2018). However, the anisotropic behaviour of this composite material cannot be derived from the combination of the material properties of both components, but requires consideration of the mutual interaction of soil and geogrid. Based on application-oriented laboratory tests such as shear, pull-out and bi- and triaxial compression tests as well as numerical simulations, numerous terms have been developed in the literature in order to describe the interaction mechanisms between soil and geogrid (Jewell et al. 1984, Palmeira 1987, Matys & Baslik 2004, Ziegler & Ruiken 2009, Lackner 2012, Jacobs 2016).

This paper gives an overview of the existing concepts of interaction and classifies them into a global and a local perspective, whereby a distinction is made between direct and indirect geogrid activation.

The behaviour of geogrid-reinforced soil can be described both by a global view of the stress-strain behaviour at macro scale and by a view of the force transmission mechanisms on micro scale. While the global approach describes the behaviour of a geogrid-reinforced soil body, the local interaction behaviour considers the force transmission between soil grains and geogrid members. In addition, the decisive factor is how the geogrid is activated. The direction of force transmission between geogrid and surrounding soil determines the type of geogrid activation.

Furthermore, the interaction behaviour depends on soil properties (density, grain size), characteristics of the geogrid (geometry, type, elongation stiffness) and given boundary conditions (stress level, load characteristics).

2 TYPES OF GEOGRID ACTIVATION

The direction of force transmission between geogrid and soil significantly influences the interaction behaviour of geogrid-reinforced soil. A distinction has to be made between two cases, for which the interaction behaviour will be reviewed on macro and micro scale:

- Case I: load transfer from geogrid to soil
- Case II: load transfer from soil to geogrid

2.1 *Case I: load transfer from geogrid to soil*

Interaction case I describes the pull-out of a geogrid from the soil. This occurs if geogrid forces are anchored in trenches or in the passive area of geogrid-reinforced retaining structures.

2.1.1 *Case I: macro scale*

The pull-out resistance of a geogrid embedded in soil has been investigated in numerous studies by Jewell et al. (1984), Palmeira (1987), Ziegler & Timmers (2003), Sieira et al. (2009) and Jacobs (2016). The relationship of tensile force against displacement of the clamp is the result of a pull-out test on macro scale.

With higher normal stresses ($\sigma_{n,A} < \sigma_{n,B} < \sigma_{n,C}$), increasing pull-out resistances are mobilized (Fig.1). The pull-out resistance has to be compared with the material strength and the smaller of the two values must be used for the design.

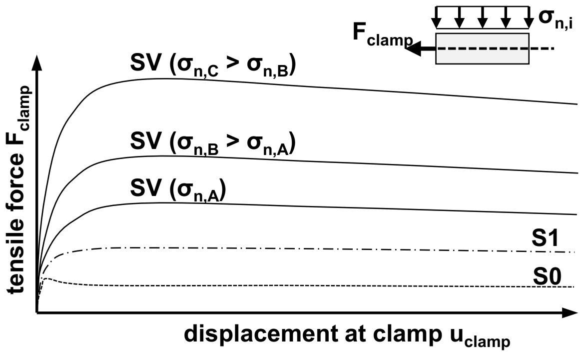

Figure 1. Qualitative results of a pull-out test

The comparison of pull-out resistances of regular geogrids (SV) to geogrids without (S0) or with only one (S1) transverse tension member provides information about the resistance components, which will be examined in more detail in the following section.

2.1.2 *Case I: micro scale*

The local force transmission mechanisms were determined as friction on the longitudinal and transverse tensile members (“skin friction” effect) and as earth resistance in front of the transverse tensile members (“bearing” effect) on the basis of S0, S1 and SV pull-out tests.

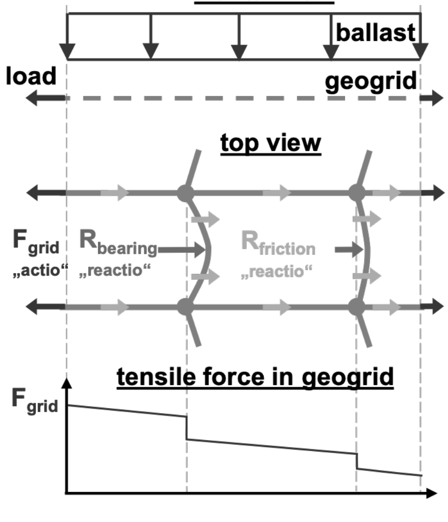

Figure 2. Force transmission mechanisms during pull-out

When the geogrid is pulled out, the soil is directly activated by the applied geogrid displacement. As a result, the tensile force in the geogrid is transferred to the soil. In this case, the geogrid displacement is at least greater than the displacement of the surrounding soil. The relative displacement between geogrid and soil decreases with increasing activated length of the grid, until the tensile force is completely transferred to the soil in case of sufficient anchorage length (Fig. 2).

Müller (2011) distinguished between flexible and rigid geogrids. While flexible grids transmit the tensile force exclusively via contact friction (“skin friction” effect), rigid grids mainly mobilize the earth resistance in front of the transverse tension members (“bearing” effect). Jewell et al. (1984) also considered the proportion of resistance caused by friction resulting from the shearing of the surrounding soil via the soil particles held in the geogrid openings (soil friction effect).

In addition, Lackner (2012) identified the “alignment” and “single string” effects of flexible woven geogrids in experimental investigations and numerical DEM simulations. The “alignment” effect describes the geometric adaptability of the geogrid to the surrounding soil particles. The “single string” effect represents the containment of soil grains in individual longitudinal and transverse tension members.

These phenomena are to be understood as subordinate effects of the main mechanisms. In the case of the “single string” effect, this is to be assigned to the “skin friction” mechanism, since the friction properties of the geogrid are influenced by the entrapped soil grains.

The anchoring of geogrid tensile forces in the soil was fundamentally described by Ziegler & Timmers (2003) and subsequently implemented by Jacobs et al. (2016) in a discrete interaction model and modelled by Wang et al. (2016) using DEM.

2.2 *Case II: load transfer from soil to geogrid*

In contrast to interaction case I, in interaction case II the geogrid is indirectly activated by a load via the surrounding soil that occurs, for example, in base layers, foundation pads or dam base reinforcements.

2.2.1 *Case II: macro scale*

Based on bi- and triaxial compression tests, the global effect of geogrid reinforcement was described as an additional confining pressure or as an increased strength.

Hausmann & Lee (1976) considered the reinforcement effect in the “cohesion concept” with an increased cohesion by parallel shifting of the failure criterion of the unreinforced soil in the τ-σ-diagram.

In contrast, the effect of the geogrid reinforcement is represented in the “confining effect concept” by an additional confining pressure $\Delta\sigma_3$ in the direction of the smaller principal stress without shifting the failure criterion of the soil.

The “confining effect” is described by various authors (Matys & Baslik 2004, Ziegler & Ruiken 2009) and can be illustrated as an alteration of the unfavourable deviatoric stress path in the unreinforced case to a path shifted in the direction of the isotropic state by the confining effect of the reinforcement (Fig. 3). As a result, the favourable deflected stress path of the reinforced soil body reaches the failure criterion at a higher stress state.

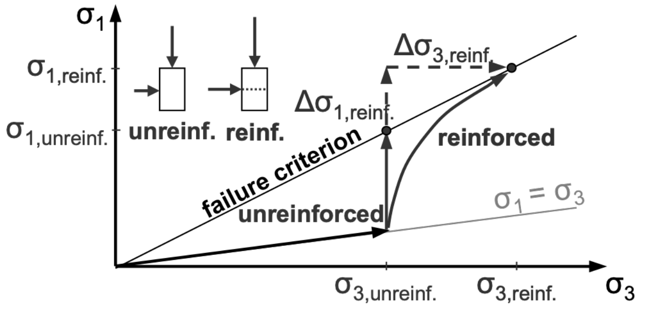

Figure 3. Confining effect concept

Ruiken (2013) investigated the stress-strain behaviour of geogrid-reinforced soil with biaxial compression tests in plane strain conditions and illustrated the positive effect of the reinforcement.

Based on the Digital Image Correlation (DIC) method, soil displacements and slip planes of specimens with and without geogrid reinforcement were evaluated in Figure 4.

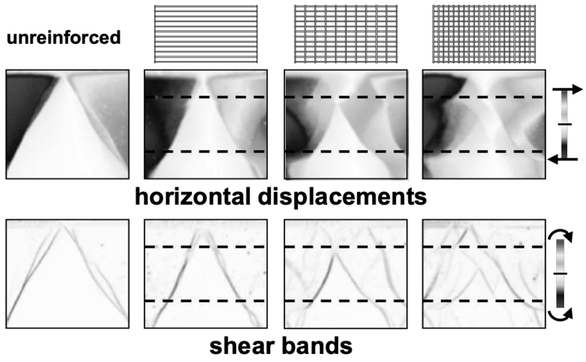

Figure 4. Results of biaxial compression tests (frontal view)

In the unreinforced specimen, the known triangular and rigid failure bodies can be identified with a lateral direction of movement. In case of the geogrid-reinforced specimens, the reinforcement creates kinematic constraints, which lead to much more subdivided bodies. Thus, more uniform deformations of the specimens and higher loads were observed with increasing number of transverse tensile members.

Moreover, the “membrane” effect is a further important global mechanism in interaction case II. The “membrane” effect is significant for geogrids in sinkhole protection systems, constructions on vertical bearing members or embankments on soft soil.

The horizontal geogrid reinforcement is activated by a vertical soil deformation. For example, the geogrid will sag in the area of the soft subsoil due to the ballast of the soil weight. The stiffness ratio between the soft soil and the bearing elements is decisive for the load distribution and determines the geogrid tensile force due to the deflection. If there is a significant settlement difference between the load-bearing elements and the surrounding soil, the geogrid has to be designed for the occurring membrane forces.

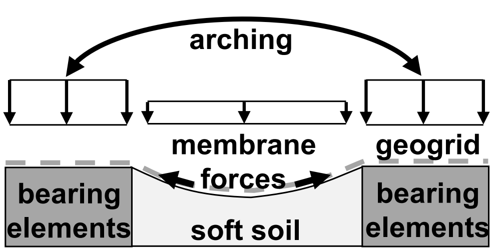

Figure 5. Membrane effect

The tensile force of the geogrid is redistributed to the lateral areas and anchored back to the soil by the mechanisms discussed in section 2.1.2.

Depending on the soil properties and the distance between the load-bearing elements, arches occur, whereby the load of the soft soil is reduced by the “arching” effect.

2.2.2 *Case II: micro scale*

While the interaction mechanisms during pull-out (case I) are sufficiently understood on micro scale, Ferreira & Zornberg (2015) described the limited understanding of the soil-geogrid interaction, especially by indirect loading in normal direction to the reinforcement (case II). In Konietzky’s (2006) opinion, the micro-mechanical behaviour of geogrids in soil is an unsolved problem, which has recently been confirmed by Peng & Zornberg (2017).

Consequently, the micro-mechanical interaction behaviour of geogrid-reinforced soil under indirect loading via the surrounding soil contains a fundamental need of research regarding the force and deformation variables.

As a hypothesis, a micro-mechanical model of the force transmission mechanisms for a uniform and decreasing load towards the geogrid ends has been developed (Fig. 6).

At the left edge, the ground is pushed over the geogrid due to the lack of lateral support, so that soil forces are transferred into the geogrid via the longitudinal and transverse tension members. This “pushout” mechanism occurs when the earth pressure acting on both sides of a vertical lamella differ from each other and thus shear forces occur. In this area, the soil displacement is always greater than the geogrid displacement.

Whereas, in the area of uniform surcharge, there is an equal support from both sides, meaning that no shear forces are created.

Here, the geogrid tensile force induced by the “pushout” mechanism is anchored back into the soil by the “pull-out” mechanism described in section 2.1.2.

After the geogrid force has been transferred to the surrounding soil, there is no further relative movement between soil and geogrid. As a result, the “interlocking” mechanism occurs in the core area of the uniformly loaded reinforcement plane, stabilizing the grain structure of the soil. Due to the interlock of coarse soil particles in the geogrid openings, increased stress states can be reached without significant deformation (Ižvolt & Kardoš 2010, McDowel et al. 2004, Ziegler 2016).

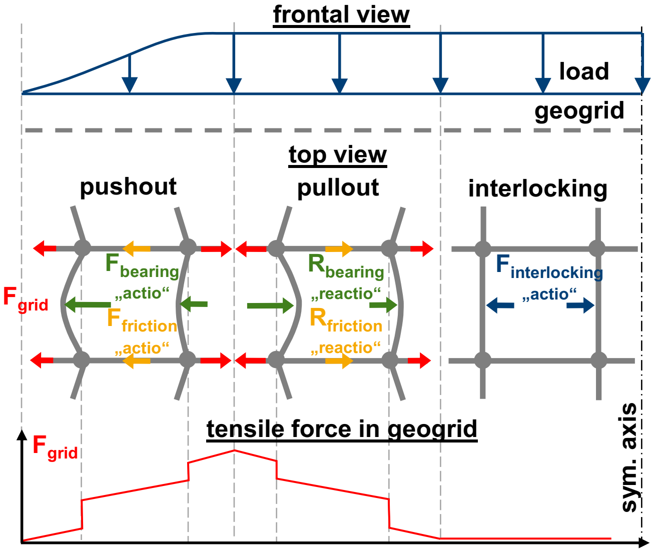

Figure 6. Micro-mechanical model for case II

Figure 6 shows the distribution of the geogrid tensile force for the developed micro-mechanical model.

However, the stiffness of the soil below the reinforcement must also be taken into account. If the subsoil is sensitive to settlements, the geogrid will expand because of deflection, as described in section 2.2.1. Then, membrane forces will also occur in the geogrid in addition to the mechanisms described above. As a result, an increased geogrid force is expected.

The shown micro-mechanical model could not be verified so far, because the soil-geogrid interface is not visible. However, non-invasive optical methods for stress and deformation measurements are now conceivable to identify the occurring mechanisms.

3 NON-INVASIVE METHODS FOR STRESS AND DEFORMATION MEASUREMENTS

In recent years, technological advances in optical imaging and computer technology have favoured the development of optical methods in geotechnical engineering (Black & Take, 2015).

Dyer (1985) recorded soil stresses during pull-out of a geogrid from a transparent medium using the method of photo elasticity and was able to visualize the earth resistance described in section 2.1.2 in front of the transverse tensile members (Fig. 7).

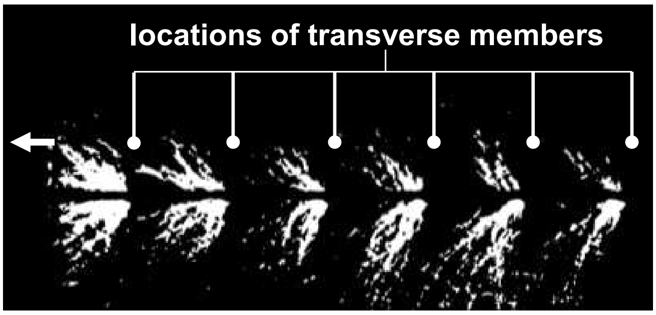

Figure 7. Light stripes during pull-out (based on Dyer 1985)

Due to the cost- and time-intensive experiments with polarized light or other methods such as magnetic resonance imaging or computer tomography, these methods were only used occasionally.

However, further developments in digital photography made it possible to record deformations using the Digital Image Correlation (DIC) method, which is often used in geotechnical experiments.

Furthermore, the development of transparent soil surrogates enabled the recording of displacements within a test specimen.

3.1 *Transparent soil*

Since natural soils are opaque, the interior of the soil body is not visible and therefore the undisturbed recording of deformations at the interface of structures in the soil is not possible.

Consequently, transparent specimens are particularly suitable for the investigation of soil-structure interactions (Ahmed & Iskander 2012).

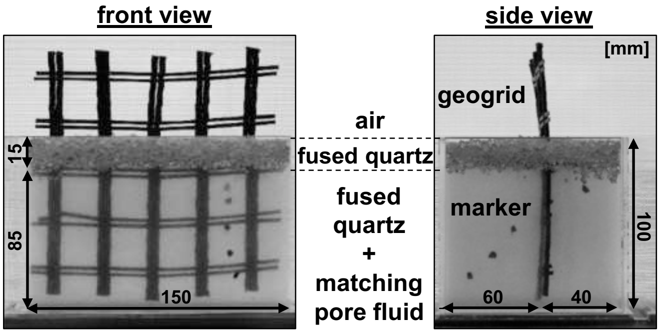

Figure 8. Transparent soil

Transparent soil is created by combining a translucent solid, usually fused quartz, with a suitable pore fluid. For the refractive index of the fused quartz (n = 1.4585), a fluid (mixture) with a matching refractive index has to be found (Iskander 2010).

The dimensionless refractive index relates the velocity of light in vacuum to the velocity of light in the corresponding medium. Light refraction takes place at the interface between two media with different refractive indices and results in an opaque sample. The refraction of light is minimized if the refractive indices of the two media are as similar as possible, which results in a transparent specimen and makes embedded geogrids visible (Fig. 8).

The good comparability of the mechanical and geotechnical properties of transparent soil with natural non-cohesive soils has been demonstrated several times on the basis of sieve analyses, compression tests, direct shear tests and triaxial compression tests (Ezzein & Bathurst 2011, Ferreira & Zornberg 2015). Moreover, no significant grain breakage of the quartz glass occurs and the influence of the high viscosity of the white oil can be neglected according to Ezzein & Bathurst (2011).

3.2 *Geogrids in transparent soil*

Ezzein & Bathurst (2014), Tatari (2016), and Peng & Zornberg (2017) recently used the investigation method with transparent soil in order to understand the mode of action in real-scale pull-out tests of geogrids from a transparent soil (case I).

This method should now also be used in interaction tests with transparent reinforced specimens to verify the micro-mechanical model presented in section 2.2.2 for interaction case II.

An insight into the geogrid-reinforced soil allows an identification of the local force transfer mechanisms at the soil-geogrid interface. In addition, this investigation method enables a non-invasive and area-wide recording of geogrid and soil displacements without disturbances caused by measuring instruments such as strain gauges or data cables as well as wall friction effects.

In a preliminary test, the principle feasibility to visualize of the soil-geogrid interaction case II was tested.

For this purpose, a transparent soil was used that consists of a fused quartz granulate (amorphous silica) and a white oil with approximately the same refractive index of n = 1.459 at 20 °C (Fig. 8).

The preliminary test was carried out in an acrylic glass box with internal dimensions of 150 x 150 x 100 mm in width, depth and height.

First, the unsaturated quartz granulate was installed in the test box and a model geogrid was placed 20 mm below the ground surface. Then, the sample was saturated with white oil under vacuum to avoid air bubbles in the specimen. Finally, the sample was loaded with a rigid plate. Meanwhile, photos were taken continuously from the front and the bottom of the box.

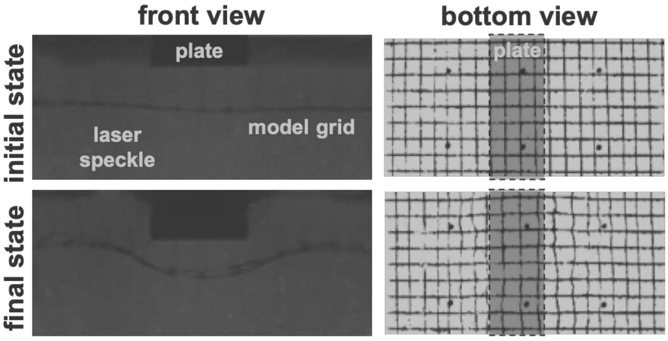

Figure 9. Soil and geogrid deformations at initial and final state

The soil deformations were recorded with the front camera using the speckle patterns generated with line lasers in the centre of the specimen. The second camera was used to record the geogrid deformations. The initial and final states of the soil and geogrid images are shown in Figure 9.

Then, the soil and geogrid displacements were evaluated based on the taken pictures using the DIC method. Figure 10 shows the displacement vectors of the soil and the geogrid in the final state.

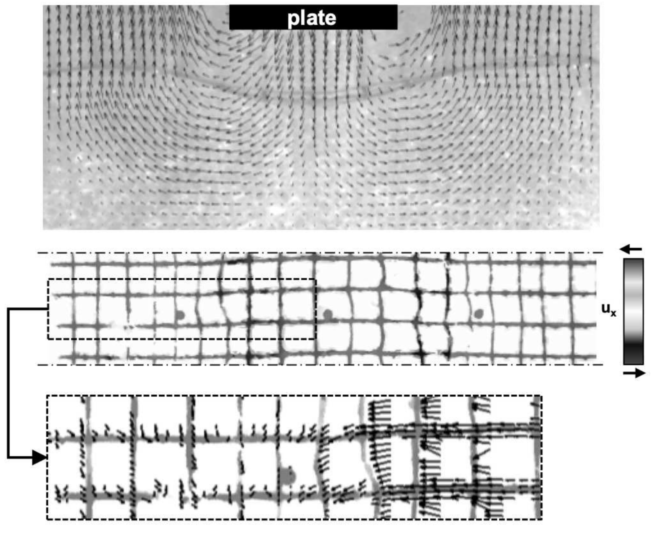

Figure 10. Soil (top) and geogrid (middle, bottom) displacements in the final state

Based on the displacement vectors of the soil the “push-out” mechanism can be identified underneath the foundation edges. Due to the vertical loading, the soil pushes the geogrid transverse members outwards, which can be seen in the displacement vectors of the geogrid.

On the other hand, the geogrid ends are pulled inwards, which means that the geogrid force is transferred into the ground by the “pull-out” mechanism.

In addition, the deflection of the reinforcement indicates that membrane forces might occur in the geogrid.

Based on the preliminary test it can be stated that interaction experiments with transparent soil are a promising investigation method for non-invasive and spatial visualization of the soil-geogrid interface. Hereby, the interaction mechanisms can be identified on micro-scale.

4 OUTLOOK

In future investigations, the interaction tests will be carried out in a larger test box with internal dimensions of 550 x 300 x 200 mm in width, depth and height and real-scale geogrids will be used in order to avoid model and scale effects.

The influences on the interaction behaviour due to geogrid stiffness, soil density, ratio of geogrid opening width to grain diameter and different lateral stresses will be investigated.

Based on the test results, mechanical approaches will be developed to describe the interaction mechanisms in case II.

Thus, a comprehensive qualitative and quantitative description of the soil-geogrid interaction is possible on micro and macro scale.

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6 REFERENCES

Ahmed, M. & Iskander, M. 2012. *Evaluation of tunnel face stability by transparent soil models*. New York: New York University.

Black, J.A. & Take, W.A. 2015. Quantification of Optical Clarity of Transparent Soil Using the Modulation Transfer Function. *Geotechnical Testing Journal.* 38(5): 588-602

Dyer, M.R. 1985. *Observation of the Stress Distribution in Crushed Glass with Applications to Soil Reinforcement*. Oxford: University of Oxford.

Ezzein, F.M. & Bathurst, R.J. 2011. *A transparent soil for geotechnical laboratory modelling*. Kingston: Royal Military College of Canada.

Ezzein, F.M. & Bathurst, R.J. 2014. *A new approach to evaluate soil-geosynthetic interaction using a novel pull-out test apparatus and transparent granular soil*. Kingston: Royal Military College of Canada.

Ferreira, J.A.Z. & Zornberg, J.G. 2015. A Transparent Soil Pull-out Testing Device for 3D Evaluation of Soil-Geogrid Interaction. *Geotechnical Testing Journal* 38(5).

Hausmann, M.R. & Lee, I.K. 1976. Strength characteristics of reinforced soil. *Int. Symposium: New Horizons in Construction Materials, Bethlehem.*

Ižvolt, L. & Kardoš, J. 2010. Parameter von Geogittern und ihr Einfluss auf deren Wirksamkeit im Eisenbahnunterbau. *Eisenbahntechnische Rundschau* 4.

Jacobs, F. 2016. Interaktionsmodell zur Bemessung von Verankerungsgräben mit Geogittern. Aachen: RWTH Aachen University.

Jacobs, F. Ziegler, M. Vollmert, L. & Ehrenberg, H. 2016. Design of geogrid pull-out with a nonlinear interaction model. *Proceedings of the 3rd Pan-American Conference on Geosynthetics, Miami.*

Jewell, R.A. Milligan, G.W.E. Sarsby, R.W. & Dubois, D. 1984. Interaction between soil and geogrids. *Polymer Grid Reinforcement.* London: Telford

Konietzky, H. 2006. Neue Erkenntnisse zur Wirkungsweise von Geogittern. *Gelsenkirchen.*

Lackner, C. 2012. *Prestressed reinforced soil - Concept, investigations and recommendations*. Graz: Graz University.

Matys, M. & Baslik, R. 2004. Study of Interlocking Effect by the Push Test. *Tectum Geosynthetic, Bratislava.*

McDowell, G.R. Harireche, O. Konietzky, H. Brown, S.F. & Thom, N.H. 2004. Discrete element modelling of geogrid-reinforced aggregates. *Proceedings of the Institution of Civil Engineers, Geotechnical Engineering.* 159: 35-48.

Müller, W. 2011. Zur Bemessung der Verankerung von Bewehrungsgittern aus Kunststoff beim Schutz von Böschungen vor hangparallelem Gleiten. *Bautechnik.* 88(6)

Palmeira, E.M. 1987. *The study of soil-reinforcement interaction by means of large scale laboratory tests*. Oxford: University of Oxford.

Peng, X. & Zornberg, J.G. 2017. Evaluation of load transfer in geogrids for base stabilization using transparent soil. *Transportation Geotechnics and Geoecology, Saint Petersburg.*

Ruiken, A. 2013. Zum Spannungs-Dehnungsverhalten des Verbundbaustoffs "geogitterbewehrter Boden". Aachen: RWTH Aachen University.

Sieira, A.C.C.F. Gerscovich, D.M.S. & Sayao, A.S.J.F. 2009. Displacement and load mechanisms of geogrids under pull-out condition. *Geotextiles and Geomembranes.* 27(4)

Tatari, A. 2016. *Interaction behaviour of soil and geosynthetic reinforcement*. Sheffield: University of Sheffield.

Wang, Z. Jacobs, F. & Ziegler, M. 2016. Experimental and DEM investigation if geogrid-soil interaction under pull-out loads. *Geotextiles and Geomembranes.* 44(3)

Ziegler, M. & Timmers, V. 2003. Neues Bemessungskonzept für die Bemessung der Verankerungslänge von Geogittern. *Geotechnik Sonderheft.* 8: 51-59.

Ziegler, M. & Ruiken, A. 2009. Materialverhalten des Verbundbaustoffs "geogitterbewehrter Boden" aus großen triaxialen Druckversuchen. *Geotechnik.* 32: 148-155.

Ziegler, M. 2016. Geosynthetic reinforcement applications. *Keynote lecture at 6th European Geosynthetics Congress*: 173-207.

Ziegler, M. 2018. Reinforcement with geosynthetics – how they work in soil. *Keynote lecture at 11th International Conference on Geosynthetics*