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Investigations on indirect geogrid activation in transparent soil

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ABSTRACT
The interaction behavior of geogrid reinforced soil is significantly influenced by the direction of force transmission between geogrid and soil. Moreover, a distinction is to be made between geogrids with a directly applied tensile force and geogrids which are indirectly loaded via the surrounding soil. In particular, the latter case of indirect geogrid activation, that occurs e.g. in base layers of embankments or foundation pads, involves a fundamental need for research with regard to forces and deformations.
This paper gives an overview of the existing concepts of interaction and classifies them into a global and a local approach, distinguishing between direct and indirect geogrid activation. Furthermore, a new test device for the investigation of the local interaction mechanisms during indirect geogrid activation is presented. For this purpose, transparent geogrid reinforced specimens are biaxially loaded, whereby an area-wide and undisturbed insight into the geogrid-soil interface is enabled. The transparent soil is created as a two-phase medium consisting of crushed quartz glass and a white oil with a corresponding refractive index. First experimental results show the displacement fields of geogrid and surrounding transparent soil, whereby the "pushout", “pullout” and "interlocking" mechanisms can be identified. The present investigations serve as a basis for soil-mechanical approaches in order to describe the interaction mechanisms and to create an interaction model for the case of indirect geogrid activation.

1. INTRODUCTION

In geotechnical practice geogrid reinforced soil has a wide range of applications. However, the anisotropic material behavior 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. Furthermore, the interaction behavior depends on soil properties (density, grain size), characteristics of the geogrid (geometry, type, stiffness) and given boundary conditions (stress level, load characteristics). 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.
In general, the interaction mechanisms significantly depend on the direction of force transmission between geogrid and soil. Therefore, in this paper a distinction is made between geogrids with a directly applied tensile force and geogrids which are indirectly loaded via the surrounding soil. Moreover, the compound behavior is described both by a macroscopic view of the stress-strain behavior of a reinforced soil body and by a microscopic view of the force transmission mechanisms between soil grains and single geogrid members.
In the first part of this paper an overview of the existing concepts of geogrid-soil-interaction on micro and macro scale is presented, whereby the type of geogrid activation is considered. In the second part, an insight into the indirect geogrid activation in transparent soil on micro scale is given.

2. TYPES OF GEOGRID ACTIVATION

For the interaction behavior of geogrid reinforced soil, it is crucial whether forces are transferred from the geogrid into the soil or are induced from the soil into the geogrid. Therefore, the interaction behavior is significantly influenced by the direction of force transmission between geogrid and soil.
In addition, an overarching consideration of the geogrid activation is conceivable, in which a distinction is to be made between geogrids with a directly applied tensile force and geogrids which are indirectly loaded via the surrounding soil. In conclusion, two cases will be considered in this paper, for which the interaction behaviour will be reviewed on macro and micro scale:

- direct geogrid activation: geogrids with a directly applied tensile force e.g. in anchoring trenches
- indirect geogrid activation: geogrids which are indirectly loaded via the surrounding soil e.g. in base layers of embankments and traffic routes as well as foundation pads

2.1 Direct geogrid activation

The direct geogrid activation basically describes the pull out of a geogrid from the soil for example in anchoring trenches. The pullout 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). In a global view of a pullout test, the relationship of tensile force against displacement of the clamp is the result on macro scale. With higher normal stresses ($\sigma_{n,A} < \sigma_{n,B} < \sigma_{n,C}$), increasing pullout resistances are mobilized (Figure 1, left). The pullout resistance has to be compared with the material strength and the smaller of the two values must be used for the design.

The comparison of pullout resistances of regular geogrids (SV) to geogrids without (S0) or with only one (S1) transverse tension member provides information about the resistance components. The microscopic 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). When the geogrid is pulled out, the soil is activated by the applied geogrid displacement. As a result, the tensile force of the geogrid is transferred into the soil (Figure 1, right). In this case, the geogrid displacement is at least greater than the displacement of the surrounding soil. As a result, during direct geogrid activation there exclusively occurs a load transfer from the geogrid into 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 a sufficient anchorage length. 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 earth resistances 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).
Furthermore, 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 simulated by Wang et al. (2016) using DEM. In conclusion, the interaction mechanisms during direct activation are well understood on both macro and micro scale.

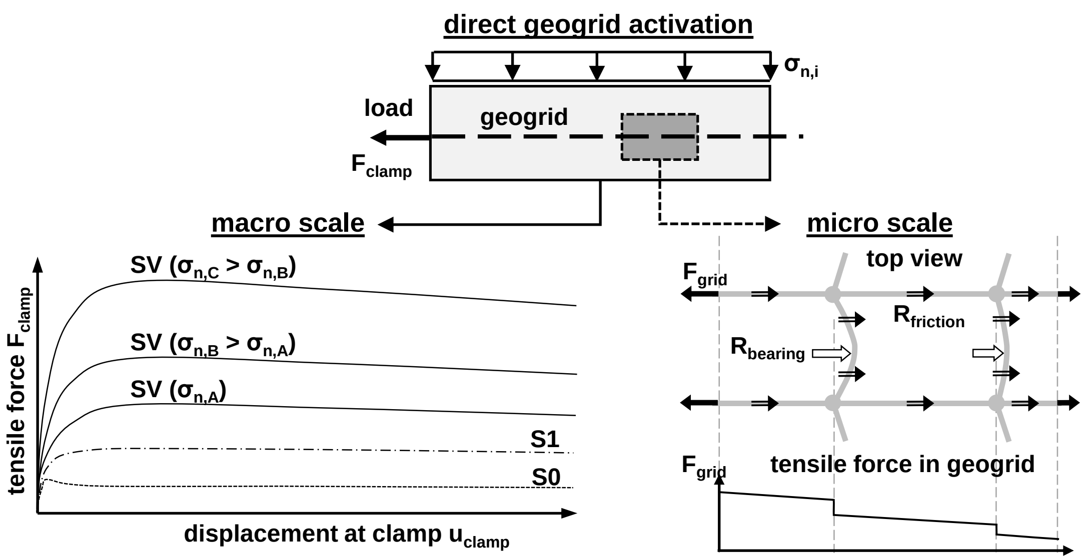

Figure 1. Direct geogrid activation on macro (left) and micro (right) scale

2.2 Indirect geogrid activation

In case of indirect geogrid activation, the reinforcement is stressed by processes in the surrounding soil. The activation of the reinforcement can result from the soil weight of the overburden, external loads or settlement differences in the subsoil. Examples of geogrid reinforced constructions in which an indirect geogrid activation is present are base layers, foundation pads or dam base reinforcements.

Based on bi- and triaxial compression tests, the global effect of indirect activated geogrids 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 to that, 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 unfavorable deviatoric stress path in the unreinforced case (continuous arrow) to a path shifted in the direction of the isotropic state (dashed arrow) by the confining effect of the reinforcement (Figure 2, left). As a result, the favorable deflected stress path of the reinforced soil body reaches the failure criterion at a higher stress state. Ruiken (2013) investigated the stress-strain behavior 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 (Figure 2, right). 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 specimen, the reinforcement creates kinematic constraints, which lead to much more subdivided failure bodies. Thus, more uniform deformations of the specimen at a higher load were observed.

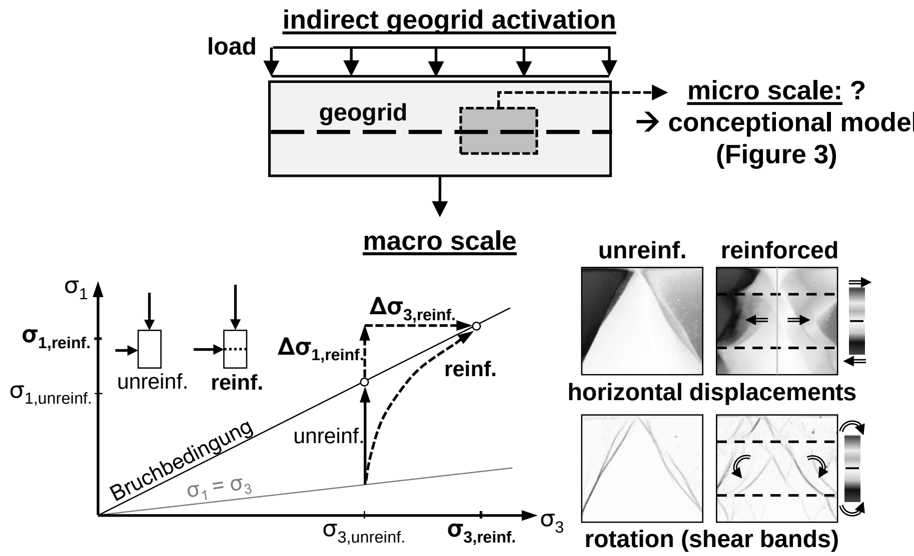

Figure 2. Indirect geogrid activation on macro scale: confining effect concept (left) and results of biaxial compression tests (right)

Moreover, the "membrane" effect is important macroscopic mechanism during indirect geogrid activation. The "membrane" effect is significant for geogrids in sinkhole protection systems, constructions on vertical bearing members or embankments on soft soils. The horizontal geogrid reinforcement is activated by a vertical soil deformation. For example, the geogrid will sag in the area of soft subsoil due to the ballast of the soil weight or external loads. 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 of the reinforcement. 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. The tensile force of the geogrid is redistributed to the lateral areas and anchored back to the soil by the "pullout" mechanisms discussed previously. As another effect on global scale, arches might occur between the load-bearing elements depending on the soil properties and geometry of the bearing system, whereby the load of the soft soil is reduced.

While the global effect of indirect activated geogrids is sufficiently understood on macro scale, there is a limited understanding of the microscopic soil-geogrid-interaction. Consequently, the micro-mechanical interaction behavior of geogrid reinforced soil during indirect activation contains a fundamental need of research in terms of occurring forces and deformation in both soil and geogrid. As a hypothesis, a conceptional micro-mechanical model for force transmission mechanisms during indirect loading of the geogrid via the soil has been developed which has to be verified (Figure 3). At the right edge area (I.), the soil is pushed over the geogrid due to the lack of lateral support. As a result, shear forces are transferred into the geogrid via the longitudinal and transverse tension members by this "pushout" mechanism. In this area, the soil displacement is greater than or equal to the geogrid displacement. In the core area (III.) of the uniformly loaded reinforcement plane, there is an equal support from both sides, whereby no shear forces are generated due to the lack of relative movement between grid and soil. Instead, the soil grains interlock in the geogrid openings ("interlocking" mechanism), so that the geogrid stabilizes the grain structure of the soil. Due to the interlock of coarse soil particles in the geogrid openings, higher stress states can be reached without significant increase in deformations (Iževolt & Kardoš 2010,

McDowel et al. 2004, Ziegler 2016). In the conceptional model it is assumed that there is a transition area (II.) between the edge (I.) and core area (III.) in which the force transferred by "pushout" mechanisms into the geogrid is anchored back into the soil by "pullout" mechanisms. As Figure 3 shows, it is not currently known whether the geogrid tensile force is completely (a.), partially (b.) or not (c.) transferred back into the soil in transition area (II.).
Moreover, the stiffness of the soil below the reinforcement must also be considered. If the subsoil is sensitive to settlements, the geogrid will expand because of deflection. Then, membrane forces will also occur in the geogrid in addition to the mechanisms described above.

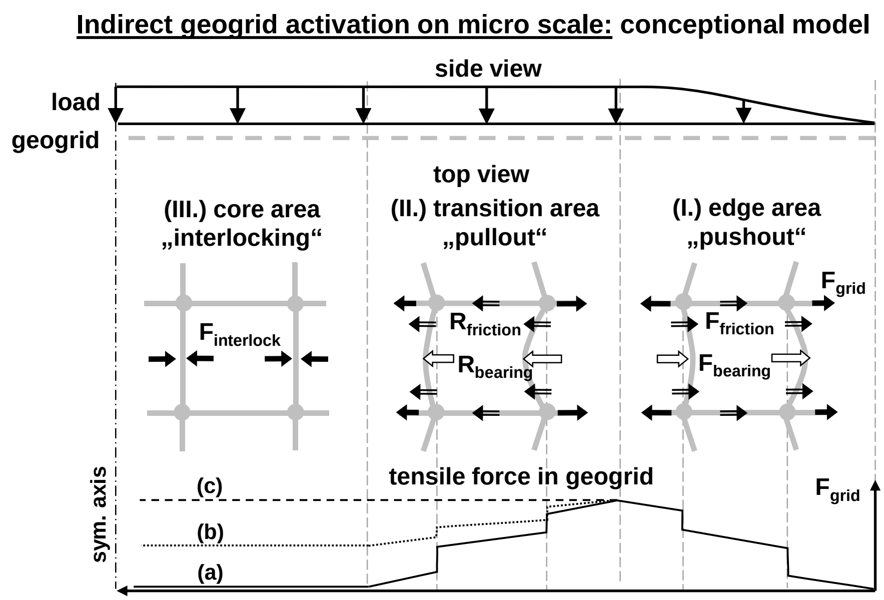

Figure 3. Conceptional model for indirect geogrid activation on micro scale

In conclusion, the authors propose the conceptional mechanical model in order to describe the indirect geogrid activation on micro scale. In contrast to the direct activation, the indirect activation does not only involve one direction of force transmission, but differentiation must be made between three areas in which the “pushout”, “pullout” and “interlocking” mechanisms occur. This model could not be verified so far, because the soil-geogrid interface is not visible in conventional investigation methods. However, non-invasive optical methods for stress and deformation measurements are now available to identify the occurring mechanisms.

3. INDIRECT GEOGRID ACTIVATION IN TRANSPARENT SOIL

3.1 Investigation method

Already in 1985 Dyer recorded soil stresses during pullout of a geogrid from a transparent medium using the method of photo elasticity and was able to visualize the earth resistance in front of the transverse tensile members. 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. In recent years, technological advances in optical imaging and computer technology have favored the development of optical methods in geotechnical engineering (Black & Take, 2015). Since then, the Digital Image Correlation (DIC) method is often used in geotechnical research to record soil deformations directly at a transparent boundary of a test box.
Since natural soils are opaque, the interior of the soil body is usually not visible and therefore the undisturbed recording of deformations at the interface of structures in soil is not possible. In recent years, transparent specimens have been used to investigate soil-structure interaction. Transparent soil is created by combining a translucent solid, usually fused quartz for representing a granular soil, with a suitable pore fluid. A fluid or fluid mixture with a matching refractive index must be found for the refractive index of the fused quartz (n = 1.4585) (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 (Figure 4).

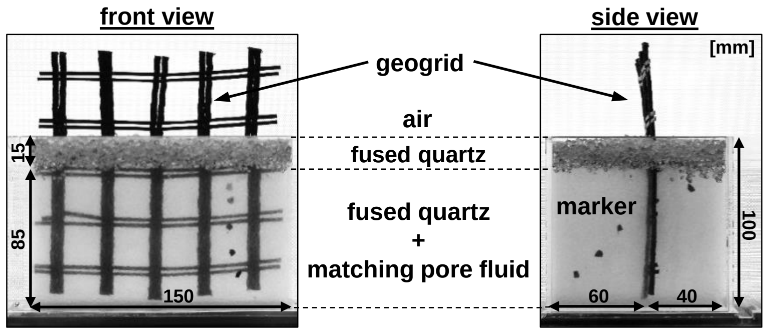

Figure 4. Example of a geogrid in transparent soil

The good comparability of the mechanical and geotechnical properties of transparent soil with natural non-cohesive soils has been demonstrated several times based on 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).
Ezzein & Bathurst (2014), Tatari (2016), and Peng & Zornberg (2017) recently used the investigation method in real-scale pullout tests of geogrids from a transparent soil in order to understand the mode of action during direct geogrid activation. The investigation method with transparent soil 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. Therefore, this method is also used in this study to get an insight into geogrid reinforced soil which enables the identification of interaction mechanism at the soil-geogrid interface during indirect activation. Based on the results, the presented conceptional model can be verified or has to be adapted according to the findings.

3.2 Materials, test specimens and new test device

A transparent soil was used that consists of a fused quartz granulate (amorphous silica) with a mean grain diameter of d_{50} = 7 mm and a white oil with almost the same refractive index of n = 1.4590 at 20 °C. Thus, in contrast to the transparent soils described in the literature, only one pore fluid could be used instead of a mixture of several oils.

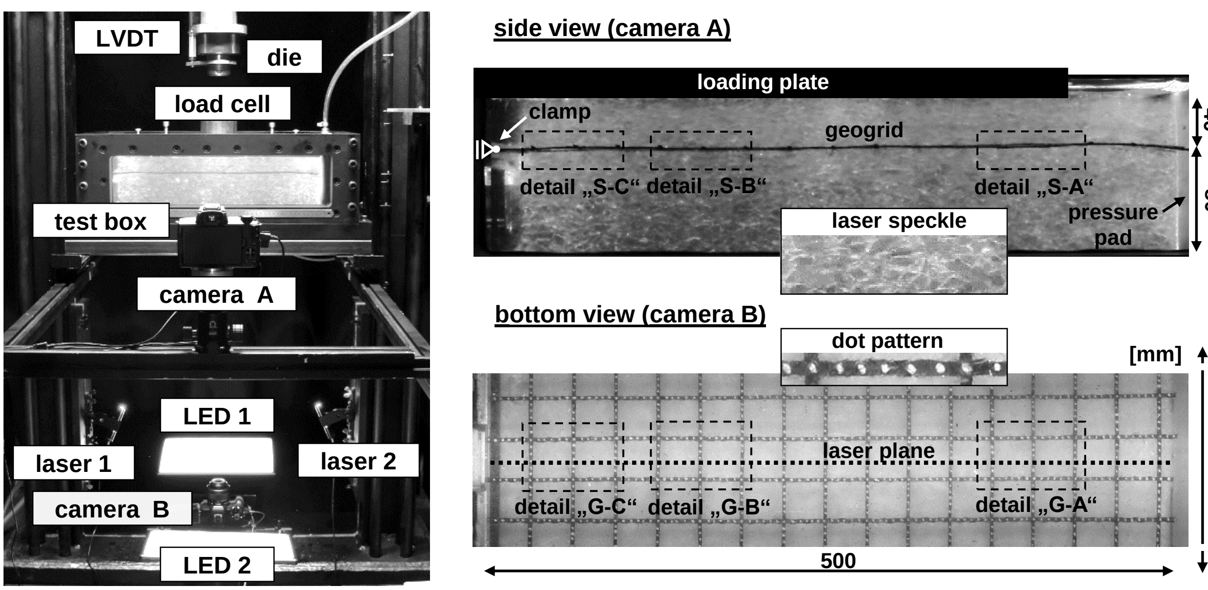

Figure 5. Final experimental setup (left) and initial state of laser plane in soil and geogrid (right)

The experiments were carried out in a box with acrylic glass windows on the front and bottom. Test specimens with dimensions up 500 x 220 x 130 mm in width, depth and height can be installed in the test box. First, the unsaturated quartz granulate was placed in the box to a height of 80 mm. Then a woven geogrid with an opening size of d_O = 30 mm and an elongation stiffness of $J_{0\text{-}2\%} \approx$ 400 kN/m was inserted and covered with 40 mm of quartz glass. The geogrid was fixed on the left side with a vertically movable clamp. On the right side of the test box, a pressure pad was arranged so that a constant lateral pressure can be applied and the soil body can deform laterally at the same time. Then, the sample was

saturated with the white oil under vacuum to avoid air bubbles in the specimen. The final experimental setup is shown in Figure 5 on the left. The test box is placed within a load frame. Above the box there is a compression die with linear variable differential transformer (LVDT) and a load cell arranged. Camera B and the lighting system, consisting of two line lasers and LED lights respectively, are located below the box and camera A is positioned in front of the box.
Finally, the sample was loaded laterally with a constant pressure of σ_3 = 1.25 kN/m² and vertically with a rigid plate in a path-controlled manner 1 mm/min. Meanwhile, photos were taken continuously from the front and the bottom of the box. The soil deformations were recorded with the front camera A using the speckle patterns generated with line lasers in the centre of the specimen. The second camera B was used to record the geogrid deformations during LED lightening (Figure 5, left). A dot pattern has been applied to the geogrid to improve contrast and to optimize the recording of geogrid deformations. The initial state of both laser plane in soil (above) and geogrid (below) are shown in Figure 5 on the right.

3.3 Test results

The soil and geogrid displacements were evaluated based on the taken pictures using the Digital Image Correlation (DIC) method. The displacement fields of the geogrid and the surrounding transparent soil are shown at the final state in Figure 6 for the sections of the edge, transition and core area shown in Figure 5.
In each area different interaction mechanisms can be identified. At the edge of the load area, the soil is pushed over the geogrid. Hereby spreading forces are transferred into the geogrid ("pushout" mechanism) which is visualized by the outwardly deflected transverse tension members of the geogrid. In the transition area, an opposite bending of the tension members can be observed, since the lateral displacements of the longitudinal members is greater than the displacement of the transverse members. This indicates an anchoring of the geogrid force in the transition area. Since there are no horizontal relative movements between the geogrid and the soil in the core area, no significant deflection of the tension members can be detected, and the "interlocking" mechanism is formed there. In conclusion, the experimental results confirm the mechanisms described in the conceptional micro-mechanical model (Figure 3).

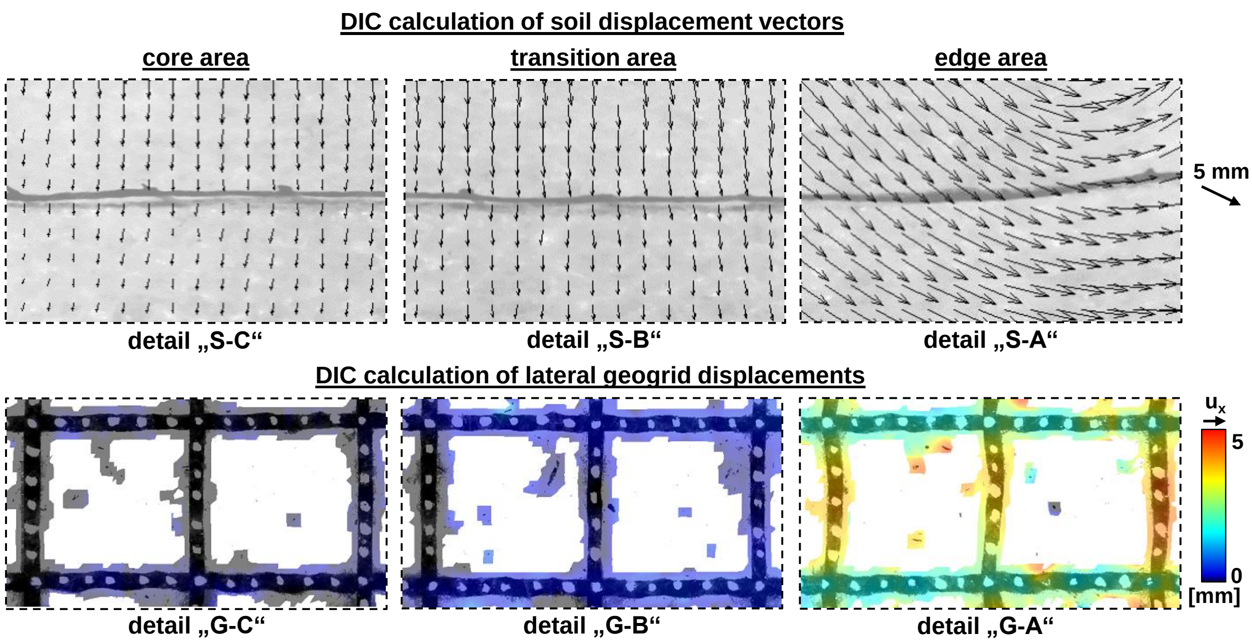

Figure 6. Soil and geogrid displacements in the edge, transition and core area at the final state

4. CONCLUSIONS & OUTLOOK

In the present research a transparent geogrid reinforced specimen was loaded perpendicular to the direction of reinforcement in order to record the interface soil-geogrid interface during indirect activation. The displacement fields of the geogrid and the surrounding transparent soil were calculated using the Digital Image Correlation (DIC) method. Hereby, the interaction mechanisms "pushout", "pullout", "interlocking" could be identified along the geogrid and the previously developed conceptional model for indirect geogrid activation on micro scale could be verified. Since the investigated type of geogrid activation is predominant in many applications of geogrid reinforcement, the findings can be transferred to these application cases. For example, geogrids in base layers, foundation pads or dam base reinforcements are indirectly activated by an applied load via the surrounding soil. Moreover, the research gives an insight into the composite material geogrid reinforced soil and visually illustrates how geogrids work. In conclusion, 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.

The next step is to derive the geogrid displacements into local strains, in order to calculate the force magnitudes along the geogrid based on the force-strain curve of the geogrid. The knowledge of the resolved force distribution along the geogrid will enable an optimal design regarding tensile strength. In further experiments, the interaction tests will be carried out in order to investigate the influences of geogrid stiffness, soil density, ratio of geogrid opening width to grain diameter and different lateral stresses on the interaction behavior. The experimental tests serve as a basis for soil-mechanical approaches in order to describe the interaction mechanisms and to create an interaction model for indirect geogrid activation. The overall objective of this research is to improve the soil-geogrid interface in finite element calculations using a stress and displacement dependent interface.

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