Relevant properties of geosynthetic reinforcements on the interaction behavior under static and cyclic load conditions

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ABSTRACT: The application of geotextiles as soil reinforcement in roads, embankments and inclined to vertical earthen wall constructions has proven a valid and very beneficial technique in the last decades. Many different products are available on the market, such as geogrids or wovens, made from different raw materials and/or using different production technologies. This paper focuses on the relevant properties of geosynthetic reinforcements on the interaction behavior under static and cyclic load conditions. In different researches and publications it has been concluded, that the ability of a reinforcement product to align itself to the soil particles or soil surface, respectively, has a beneficial effect on the interaction behavior. Especially under cyclic loads, such as in road or railway applications, the capability to align has been shown beneficial. The paper gives an overview on related literature and explains the beneficial effect of a high alignment capacity of reinforcement products on the performance of the composite material "reinforced soil".

Keywords: adaptability, flexible geogrids, interaction flexibility

1 INTRODUCTION

Although geosynthetics are successfully used since decades to reinforce earth structures the complex interaction behavior between soil and geosynthetic is still under investigation. It is the general understanding that the three main characteristics of geosynthetic reinforcement products, which dominate the performance of the compound material "geotextile reinforced earth", are the tensile strength, tensile modulus as well as the interaction behavior with the soil.

Tensile strength is quite obvious, since in most reinforcement applications a strength deficit has to be balanced by the geotextile reinforcement. The required strength can be estimated based on limit equilibrium methods, such as slip circles with e.g. the method of Bishop (moment equilibrium) or the block sliding method (force equilibrium).

Furthermore, to ensure a limitation of deformation of the geotextile reinforced earth structure to an acceptable or required level a certain tensile modulus of the geotextile reinforcement is required. Attention should be paid to the relation between tensile modulus of the reinforcement and the stress strain behavior of the soil. Several researchers illustrated the dependency of the mobilized tensile strength of reinforcement on the strain level in the reinforcement and soil. Jewell (1985) found that the required and available forces vary with the level of mobilized strain in backfill and reinforcements. Therefore, a sustainable internal equilibrium for an optimized design requires the compatibility of the required force with the available resistance (mobilized shearing resistance in soil and tensile strength in reinforcement) at working strain level. Consequently, Jewell (1986) showed that an adequate design of the reinforced wall should ensure that the design values chosen for the reinforcement and the shear strength of backfill material are mobilized together whereas the equilibrium is guaranteed with acceptable deformation in the structure. A numerical investigation on this can be found in Detert et al. (2016).

The third component, interaction behavior, describes the “communication” between the soil and the geotextile reinforcement. The ability of the geotextile to take forces from the soil and to transfer them over certain distances back into the soil is very important for the overall performance. Following section reports in more detail on the influencing geosynthetic characteristics on the interaction behavior.

2 LITERATUR REVIEW ON THE GEOSYNTHETIC CHARACTERISTICS REGARDING THE INTERACTION BEHAVIOR

Different publications report on research results regarding the different geosynthetic characteristics influencing the interaction behavior.

2.1 *Geometrical factors*

In case that a kind of pull out or shear mechanism is activated, an influence of the cross members on the pull out or shear force can be observed. This is explained by a passive earth pressure which develops in front of the cross members, when they are pulled through the soil. To active those force contribution a certain displacement has to take place. Ziegler and Timmers (2004) analyzed this contribution of the geogrid cross members with systematic pullout tests. They conducted tests with and without cross members of the geogrid and observed a significant increase in pull out resistance. The extent of this contribution depends on the magnitude of the transferable forces at the crossing points of the cross and longitudinal strands of the geogrid. Figure 1 shows the deformed cross members of a woven geogrid after a pull out test. The deformations are an indication of the developed passive earth pressure resistance in front of the cross members.

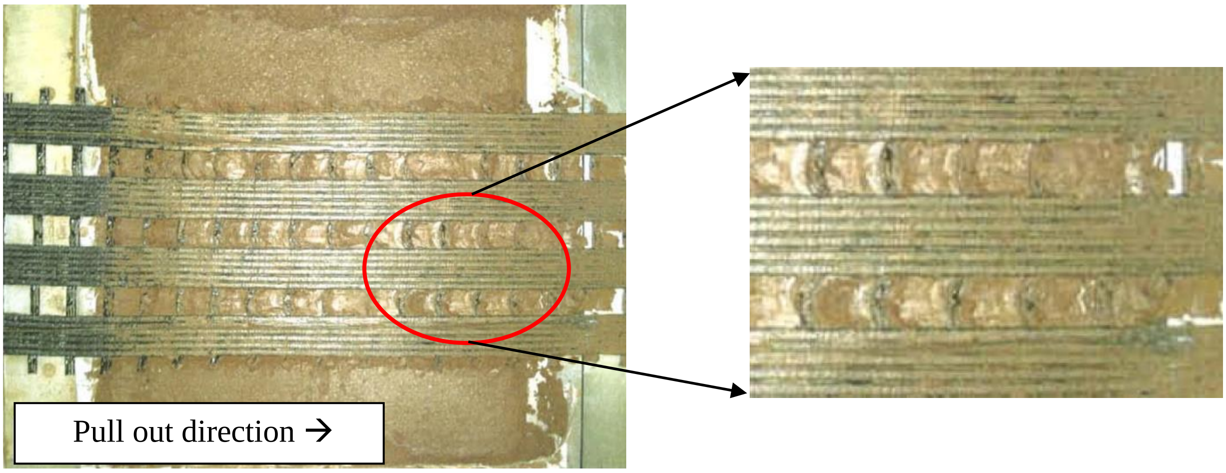

Figure 1. Deformed cross members of high strength woven geogrid

Among other Izawa et al. (2001) investigated the influence of the geometry of the geogrid by varying the distances between the geogrid members and their thicknesses. They concluded, that the thicker the cross members are, the higher is the positive effect on the pull out resistance.

The effect of the opening size of a geogrid on the interaction behavior in pull out and shear mode has been analyzed by different researches, such as e.g. Jewell et al. (1987), Sarsby (1985) or Lopes and Lopes (1999). An influence between the ratios of particle sizes (e.g. d_{50}) and the opening size of the geogrids was found.

2.2 *Mechanical factors*

Schlosser and Elias (1978) analyzed the influence of the surface roughness and concluded that the transferable shear stress between soil and geotextile increase with increasing roughness of the surface.

Stoewhase (2001) identified the surface hardness as a further influencing parameter. The more the soil particles can penetrate into the geotextile, the higher the transferable shear stresses. O’Rourke et al. (1990) also noticed that the maximal shear strength in the interface between soil and geotextile decrease the harder the surface of the geotextile is.

A further influencing property on the interaction behavior is the bending stiffness of the geotextile. Also the bending stiffness of all geotextiles currently available in the market is very small or even negligible in comparison to e.g. steel grids an influence has been identified.

Lees (2014) experimentally measured the influence of a so called “punched and drawn” geogrid on the shear strength of the composite material from granular material and geogrid. He reinforced a soil sample with one geogrid layer and conducted direct shear tests at different levels above the geogrid layer. Up to a distance of 30 cm he could detect a positive effect on the shear strength in comparison to the shear strength of the granular material itself. An increased shear strength of the material has been observed in a distance of 20 cm, 10 cm and 5 cm above the geogrid. But in a shear plane 1 cm above the geogrid the shear strength of the composite material was even reduced compared to the unreinforced sample. It was concluded, that this may be based on the lower soil density in the zone directly around the geogrid and could have been overcome with higher compaction energy. In this case the geogrid has prevented a high density of the granular material, which results most probably from its bending stiffness.

Lackner (2012) investigated the interaction between soil and geogrid in a mesoscopic scale. Amongst others things he investigated the behavior of reinforced and unreinforced gravel layers in a test box under cyclic load conditions. The load conditions changed in frequency and amplitude and represent the load conditions within a certain depth beneath a railway track. The front side of the test box was moveable. It was supported by a force corresponding to the earth pressure at rest or even a reduced earth pressure at rest. The vertical settlements of the granular material was measured over the load cycles respectively time. As failure criteria a certain horizontal deformation of the moveable front wall was defined. In his test set-up he analyzed an unreinforced and two reinforced samples. The used geogrid reinforcements are made from PET and had about the same ultimate tensile strength. One geogrid is produced from extruded strands which are welded together (rigid geogrid), the other geogrid is a woven product from multifilaments which has been coated after the weaving process (flexible geogrid). Figure 2 shows the results from the above described tests.

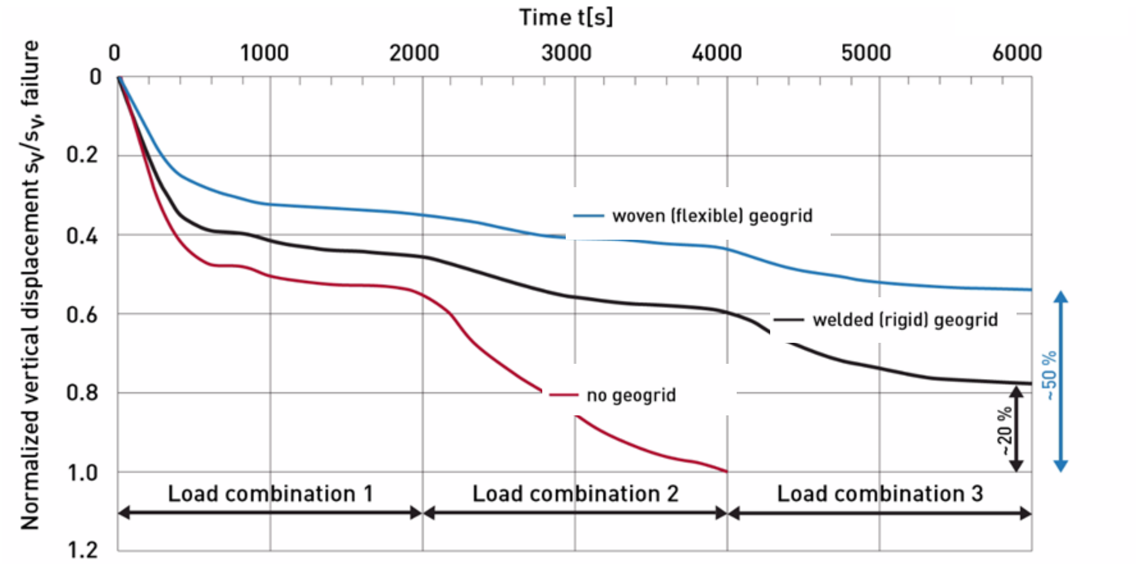

Figure 2. Normalized vertical displacement for an unreinforced sample, a reinforced sample with a rigid geogrid and reinforced sample with a flexible geogrid (Lackner 2012)

The vertical displacements (y-axis) are normalized by the maximum vertical displacement of the unreinforced sample at failure. On the x-axis the time is shown, which corresponds to a certain amount of cycles for the different load combinations. As shown in figure 2, the unreinforced test set-up did fail at the end of the second load combination. No failure occurred with the reinforced samples. Although the ultimate tensile strength of the used geogrids have been equivalent and the tensile modulus of the welded (rigid) geogrid has been higher than the tensile modulus of the woven (flexible) geogrid, the overall performance of the woven (flexible) geogrid under cyclic loading has outperformed the welded (rigid) geogrid. As shown in figure 2 a reduction of the total settlement of about 20% has been reached with the rigid geogrid and about 50% with the flexible geogrid.

Based on this unexpected results a more detailed analysis of the interaction behavior has been conducted. By means of the discrete element method the laboratory tests were modelled and simulated very detailed. From this numerical analysis he reported three main interaction components are activated in soil-geotextile contact, namely (i) frictional interaction between the soil particles and the surface of the geogrid, (ii) interlocking of the soil particles between the discrete members of the geogrid, (iii) the alignment effect. The third component deals with aligning the reinforcement around the soil particles (Figure 3).

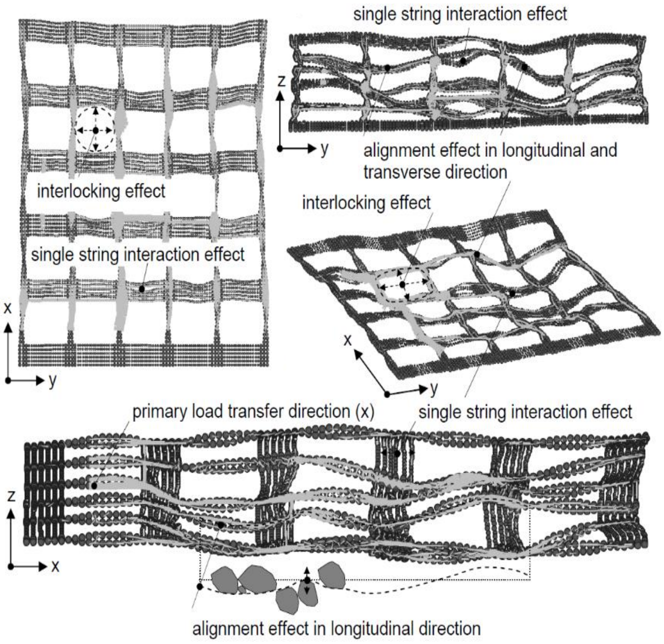

Figure 3. The interaction modes of a flexible geogrid with the soil due to different resistance components in mesoscopic scale from discrete element modelling (Lackner 2012)

He concluded, that the alignment of the geogrid does improve the interaction between geogrid and soil and that therefore the flexible geogrid performance better (Lackner 2012).

2.3 *Deformation depending contribution of the different properties and mechanism*

The share of the described properties and mechanism on the interaction behavior depends on the state of deformation in the composite material. To mobilize the passive earth pressure in front of the cross members of a geogrid a relative huge deformation needs to occur. Friction between the soil and the surface of the geogrid is activated much earlier. According to Alagiyawanna et al. (2001) is the contribution of the surface friction in the service state of the structure much higher than the contribution of the earth pressure in front of the cross members. The interlocking mechanism even does not need any deformation after installation and compaction of the granular material.

3 DISTINCTION IN THE INTERACTION BEHAVIOR OF FLEXIBLE AND RIGID GEOGRIDS

Flexible geogrids have the capability to adapt to the shape of the particles and surface, respectively. No voids or small cavities are preserved below the geogrid (Figure 4).

A higher flexural rigidity enables the geogrid to bridge small distances like a couple of centimeter between adjacent stones and small cavities remain. As a consequence compaction energy or actions from the traffic are responded by an elastic behavior of the composite material due to the fact that the small “bridges” respond like elastic springs.

Figure 4. Alignment of a flexible geogrid to the particles and surface, respectively.

In contrast flexible geogrids do allow the material to reach a state of higher density (more contact points between the grains) and therefor a state of higher shear strength. At the same time flexible geogrids, if aligned to the surface, do provide horizontal and also vertical resistances to the particles due to the deviation of the axial tensile forces. This does lead to firm confinement of the particles and restriction of movements, so less deformation in the structure will occur.

Figure 5 shows schematically the increase in contact area for a flexible geogrid by adapting to the particle shape in contrast to a rigid geogrid.

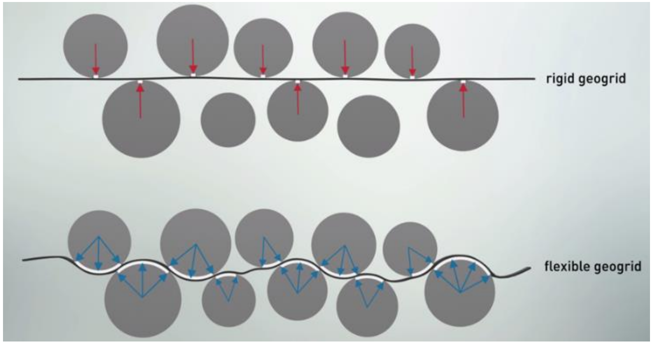

Figure 5. Contact area between particles and rigid or flexible geogrids

Due to the significantly higher contact area between the soil particles and the geogrid the interaction between the soil and the reinforcement does increase, more shear stresses can be transferred from the soil into the reinforcement and vice versa due to the increased contact area.

This could be compared with the well none effect described by the formula of Euler-Eytelwein (Figure 6), which explains why a force F_2 can be balanced with a smaller force F_1 when e.g. a rope is wrapped around an item. Friction acts along the contact area between the rope and the item, e.g. a roll, and reduce the required force F_1 to balance the force F_2.

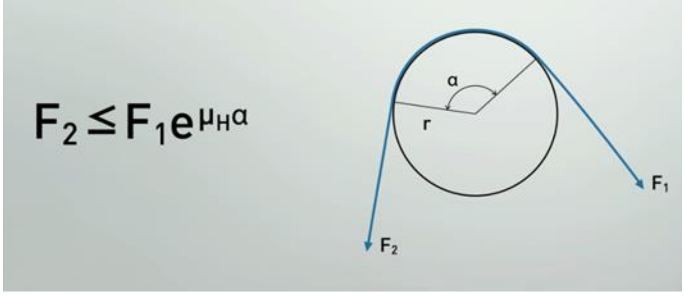

Figure 6. Formula of Euler-Eytelwein: Due to the friction along the contact area describe by the angle alpha and radius r a force F2 can be balanced by a smaller force F1

Althoff (2015) analyzed the interaction behavior of 12 different reinforcing products in 3 different soil types by pull-out and direct shear tests. Woven, layered and drawn geogrids have been used in the test. Table 1 shows the statistical evaluation of direct shear tests with woven and layered geogrids in the same granular material.

Table 1. Statistical evaluation of direct shear tests of woven and layered geogrids using the same granular material (Althoff, 2015)

Geogrid type	Interaction coefficient
Woven	0,94
Layered	0,82
Layered	0,91
Woven	≥1,0
Woven	≥1,0

As a general tendency of the executed tests in his research the woven geogrids reached slightly to significant higher (Δ ≥ 10%) coefficient of interaction in comparison to layered or punched geogrids.

4 SIGNIFICANCE OF INTERACTION BEHAVIOR UNDER STATIC AND CYCLIC LOADING

One of the main differences in static or cyclic loading is the permanent triggered particle movement under cyclic loading.

For static load conditions a certain state of equilibrium is reached mostly already during the construction process (in the case that no further deformation occur e.g. due to consolidation settlements or similar external influences). The relative positions of the granular particles among each other and in relation to the reinforcement are reasonably fixed. Therefore the number of contact points between the particles, where shear stresses can be transferred, are constant. A further densification will occur when external laods subside the activated internal shear strength. Due to the densification the number of contact points does increase and higher shear stresses can be activated.

A different situation occurs under cyclic loading. Due to the permanent change in load conditions the stresses in the contact points do change constantly. If the cyclic induced shear forces do exceed the maximum shear strength of a contact point, this contact point plasticize and the particles will rearrange into a more stable arrangement, unless they are somehow hindered. This is comparable with the compaction process where the voids between the single particles are minimized to increase the contact points of the granular particles to each other. The result of the plasticization of different contact points and the consequent rearrangement of the particles are deformations and an increase in density and therefore in the total amount of contact area, which does lead to higher shear strength. The deformation rate may decrease over time, if an arrangement can be achieved to withstand the cyclic induced shear stresses. If those external loads are somehow responded by a partial elastic response, particles may move but do not necessarily reach the required dense state to withstand the external in the next load cycle. An ongoing deformation of the structure will occur, as it can be seen in figure 2.

5 CONCLUSION

The adaptability of geogrids to the particles or ground surface is beneficial for the load transfer between soil and reinforcement. The effect can be especially observed under cyclic loading, where the flexibility of the geogrid allows the material to reach a high density and little or none cavities remain. At the same time the particles are confined due to the alignment of the geogrid and the resulting deviation of the tensile forces, which leads to horizontal and vertical components.

Rigid geogrids in contrast, are capable to bridge small distances between particles. Those small bridges and the remaining cavities result in partially elastic response to actions, since those bridges are acting like springs.

The main properties and characteristics of a geogrid as reinforcement are tensile modulus, tensile strength and the interaction behavior with the soil. As reported above, the interaction behavior is dominated by the frictional interaction, interlocking and also the adaptability of the geogrid to the unevenness of the soil surface or particles. The capability of a geogrid to have frictional interaction and interlocking with soil in combination with the adaptability to unevenness can be named “interaction flexibility”.

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