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Prestressed reinforced soil for infrastructure projects – a microscopic research

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Abstract. In this paper, investigations on prestressed geogrids installed to reinforce embankments for motor- and railways are presented. A microscopic three dimensional (3D) model using the Discrete Element Method (DEM) is constituted to evaluate displacements and contact forces between discrete gravelly particles in a prestressed reinforced soil element. The granular soil particles and the discrete geogrid reinforcement were numerically modeled by "Computer Aided Design" (CAD). The load transfer mechanism between the soil particles and the geogrid reinforcement was evaluated. Arching effects occurred randomly between the granular soil particles and the discrete longitudinal and transverse members of the geogrid. These arching effects lead to local force concentrations between the generated particles and to high tensile forces in the numerically bonded geogrid. In addition, three soil geogrid interaction effects were determined. In the case of discrete clumps entering the gaps of the discrete geogrid, the longitudinal and transverse members of the reinforcement were expanded. This effect had already been classified as static or dynamic interlocking effect in literature. While loading the reinforced soil element, grains also entered between the single strings of the longitudinal and transverse members of the woven geogrid reinforcement. This effect was newly defined as single string interaction effect. In longitudinal but also in transverse direction the geogrid aligned to the surrounding granular particles. This newly defined alignment effect led to a permanent contact between geogrid and soil particles and thereby resulted in a permanent interfriction effect. The provided numerical model gave a realistic and detailed insight in the fundamental load transfer and soil geogrid interaction behavior in case of utilizing the concept of prestressed reinforced soil for innovative infrastructure projects.

Keywords: prestressed reinforced soil, geogrid, discrete element, clump, microscopic

1 INTRODUCTION

The requirements to geogrid reinforced soil structures are increasing rapidly. As opposed to conventional infrastructure construction methods, reinforced soil structures sometimes do not behave strongly and stiffly enough. Developing and validating a system to easily increase the bearing capacity of the geogrid reinforced soil structures and to improve their deformation behaviour is the objective of the ongoing research task PRS_i. Working out design and construction methods for reinforced soil structures utilized for infrastructure projects and scientifically validating these recommendations by microscopic numerical investigations is the objective of this paper.

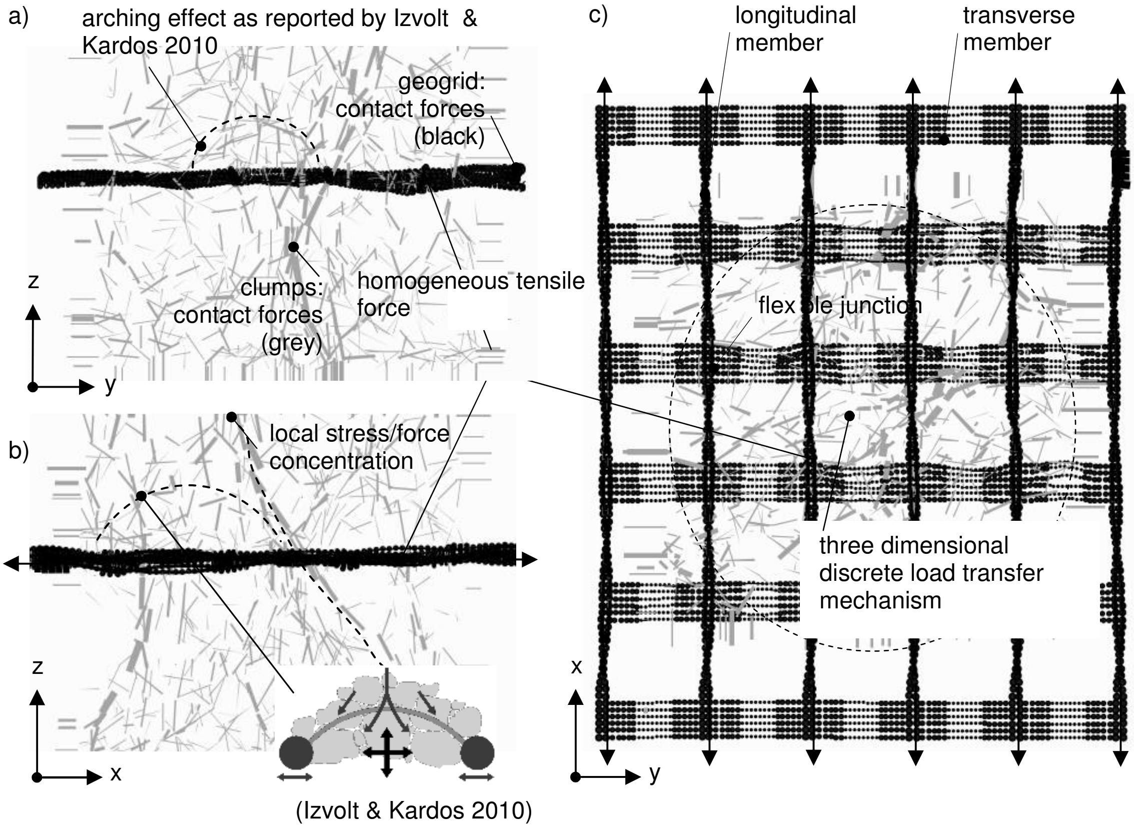
2 DEM MICROSCOPIC RESEARCH

2.1 Numerical Model and Parameters

In this chapter, investigations on prestressed reinforced soil utilizing Discrete Element Method modelling are presented. As pointed out in Lackner (2012) a three dimensional (3D) Discrete Element model is constituted to evaluate displacements and contact forces between discrete particles in the reinforced soil structure. A cube with a side length $a = 0.1$ m represents a soil element. This element is numerically simulated. Basics, the overview on the numerical model and its numerical parameters is presented in detail (Halsegger 2004, Zöhrer 2006, Scharinger 2007, Lenzi 2009, Lackner 2012, Dijak 2012).

2.2 Numerical results and discussion

Figure 1 shows the load transfer mechanism of the permanently prestressed reinforced (PRS_p) soil element. Again a so called arching effect (Izvolt & Kardos 2010) becomes visible (Fig. 1 a) and b). This effect results in local stress concentrations between the soil particles. The tensile force of the geogrid distributes constantly along the reinforcement in the longitudinal (x) direction. This is due to the permanently prestress in the longitudinal direction.



mesoscopic information
soil: 488 clumps _6037 spheres_9 contacts/clump_2 active contacts geogrid: 4332 spheres_5046 bonds

Figure 1: DEM mesoscopic modelling of a permanently prestressed reinforced (PRS_p) soil element to evaluate the mesoscopic load transfer mechanism: a) side view (y-z) including contact forces between the granular particles and tensile force distribution along geogrid b) front view (x-z) including contact forces between the granular particles and tensile force distribution along geogrid c) plan view (x-y) including contact forces between the granular particles and tensile force distribution along geogrid.

As opposed to the longitudinal forces in the geogrid the tensile forces in the transverse members of the reinforcement are low. Figure 1c) shows the random three dimensional load transfer mechanism in the plan view.

Once, the mesoscopic deformation behaviour of the prestressed reinforcement is investigated. Figure 2 shows three effects. In the case of reinforcing the soil element conventionally, interlocking effects are visible. This is also true when the geogrid is prestressed (Figure 2 a).

Figure 2 b) and c) show a high quantity of single string interaction, mainly in the transverse members. This is due to the prestress of the geogrid in longitudinal direction. The transverse members are strained in x direction. Thereby, the discrete clumps can easily access between the single strings.

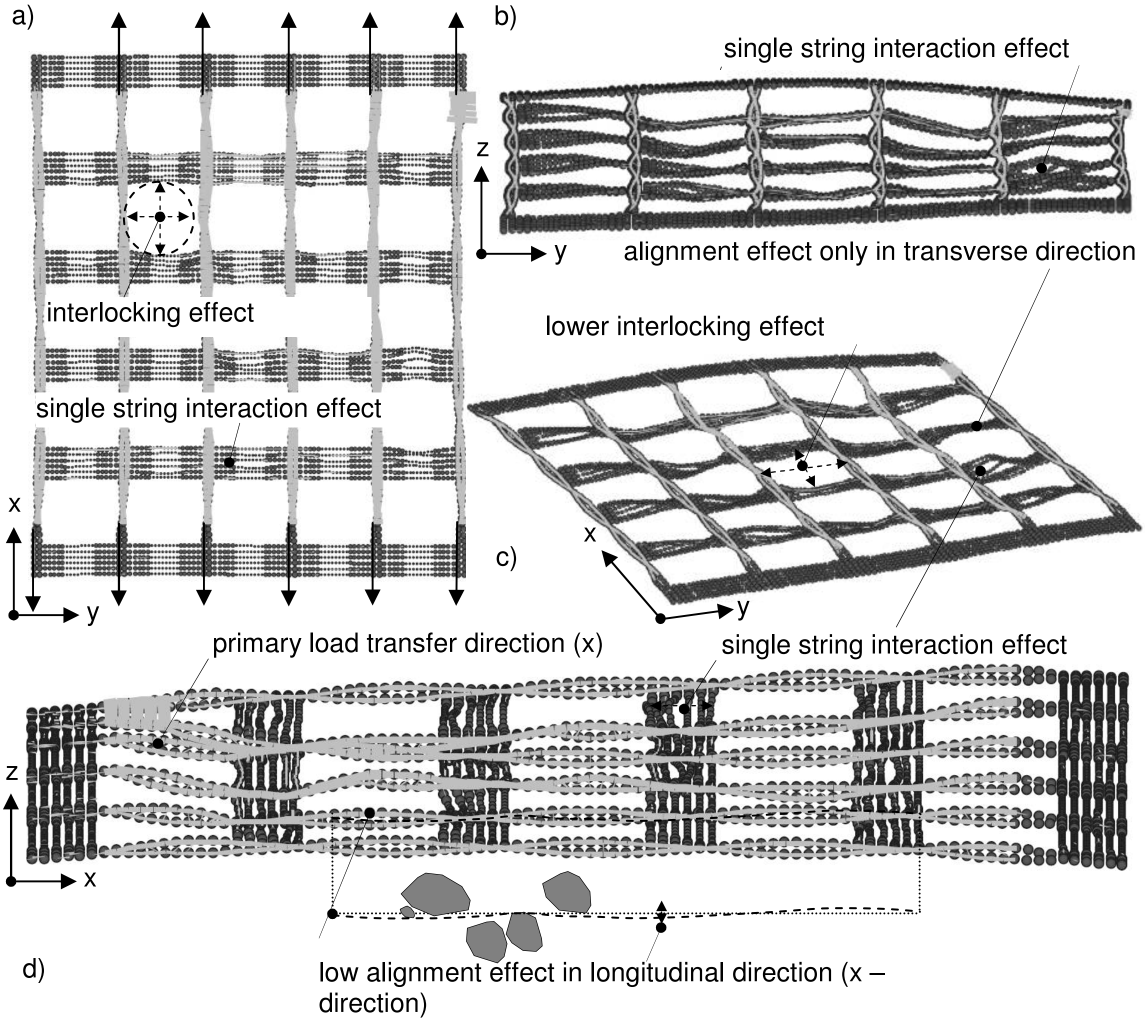


Figure 2: DEM mesoscopic modelling of permanently prestressed reinforced (PRS_p) soil element to evaluate the mesoscopic deformation of the geogrid reinforcement: a) plan view (x-y) of the geogrid including tensile force distribution along geogrid and interlocking effect b) side view (y-z) including tensile force distribution along geogrid and single string interaction effect c) 3D view (x-y) including tensile force distribution along geogrid d) front view (x-z) including tensile force distribution along geogrid and alignment effect.

Figure 2d) shows the soil geogrid interaction by alignment. It is visible that the geogrid does not highly align around the particles in the longitudinal direction. This is again due to the prestress in the reinforcement. As shown in Figure 2d) this may results in gaps between the reinforcement and the surrounding particles. Further, this results in lower interfriction between soil and reinforcement. The concept of prestressed reinforced soil usually results in an improvement of the soil structure. Although positive interaction effects such as the alignment effect, may be sometimes reduced.

It can be stated that the macroscopic results from the numerical DEM analysis show a sound agreement with the experimental investigations (Lackner et al. 2013) and the FEM simulation presented in Lackner (2012). Additional mesoscopic analyses show the load transfer mechanism between soil and reinforcement in detail. Three effects have been observed and defined. They mesoscopically explain the positive consequences when utilizing the concept of PRS_i. As a final conclusion it can be stated that the soil geogrid interaction can be simulated well by utilizing the innovative concept of CAD clumps and geogrids for DEM simulations.

3 APPLICATION FOR INFRASTRUCTURE PROJECTS

In order to implement the fundamental research results in to an effective construction method the following chapter presents practical design and construction recommendations. Permanent prestress is induced to a geogrid reinforcement by applying the following recommendations.

3.1 Design recommendations

In order to apply the required prestress to the geogrid, the geometry of a so called prestress trench has to be calculated (Figure 3). Table 1 presents the depth h_t of the prestressing trench exemplarily for a 10 m long geogrid necessary to activate prestress strains of ε_{PRSp} = 1.0 to 3.0 % (Lackner 2012).

Table 1: Depth h_t of prestressing trench: Length of geogrid before compaction the trench: e.g.: $l_{geogrid}$ = 10 m.

Prestress strain of geogrid ε_{PRSp}	1.0	1.5	2..0	2.5	3.0	Unit [%]
Slope angle of prestress trench β						[°]
30	18,7	28,0	37,3	46,7	56,0	[cm]
35	15,9	23,8	31,7	39,6	47,6	[cm]
40	13,7	20,6	27,5	34,3	41,2	[cm]
50	10,7	16,1	1,4	26,8	32,2	[cm]
60	8,7	13,0	17,3	1,7	26,0	[cm]

The depth of the prestress trench changes with respect to the slope angle β of the trapezoidal trench. The smaller the slope angle β, the deeper the prestress trench. The depth of the prestress trench increases rapidly if the slope angle β decreases.

As reported in the literature it is recommended to fix the geogrid by simply dumping backfill material on to the reinforcement. The anchorage length L_A to fix the geogrid properly is calculated by employing the equation 1.

$$L_A = \frac{T_{PRSi}}{\sigma_v \cdot \tan\varphi \cdot R_{inter} \cdot n} \quad (1)$$

T_{PRSi} represents the tensile force in the prestressed reinforcement. In order to calculate shear stresses along the interaction zone, the vertical stress σ_v has to be multiplied with the tangent of the friction angle φ and the soil geogrid interaction coefficient R_{inter}. The shear stresses generally occur on both sides of the geogrid (n = 2) in the case of the geogrid is pulled out.

3.2 Construction recommendations

In the case of utilizing the concept of PRS_p, a prestress trench is well applicable to tighten the geogrid (Chew et al. 2005, Alfaro et al. 2006). Figure 3 presents the side view of the construction recommendation. First, the reinforcement is placed tightly on the subsoil layer and the pre-constructed prestress trench (Figure 3 a). Then, the geogrid is fixed at both ends, either by dumping the geogrid with backfill material or by using steel benders, according to Figure 3 a).

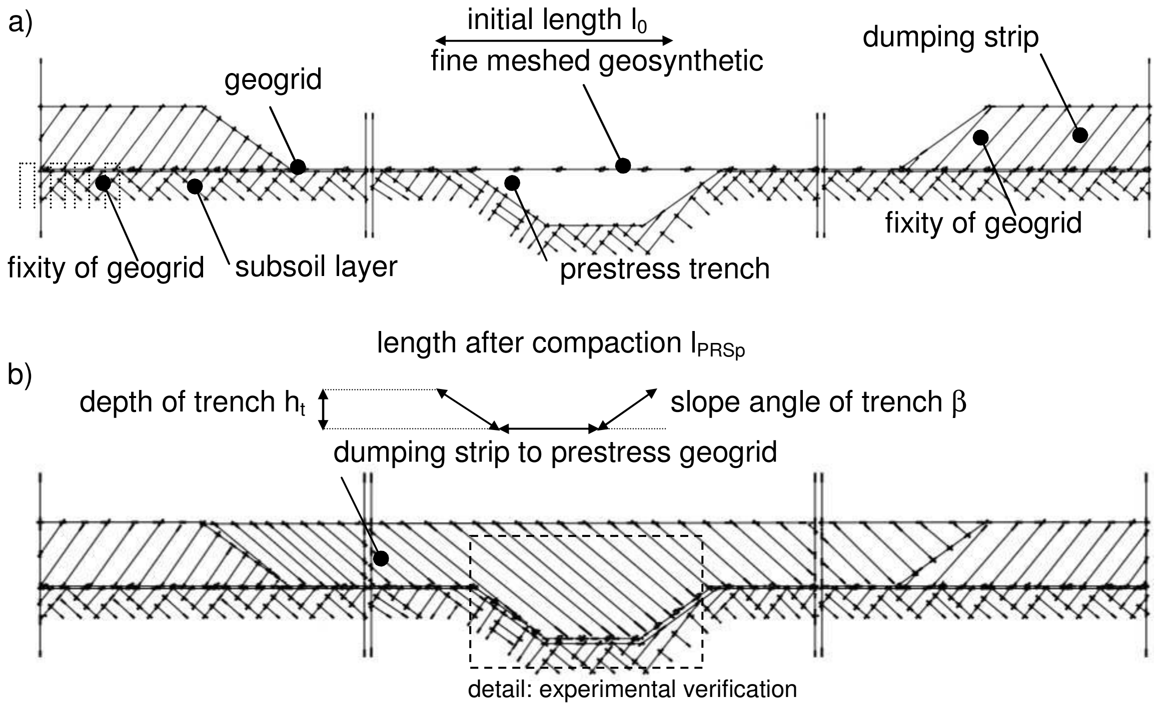


Figure 3: Geogrid prestressing with prestressing trench: a) side view of the prestressing procedure before dumping the prestressing strip b) side view of the prestressing procedure after dumping the prestressing strip (modified according to Havinga 2012).

Finally, the actual soil layer is dumped and compacted (Figure 3 b). Thereby the geogrid aligns along the prestress trench and a permanent prestress is activated.

4 SUMMARY AND CONCLUSIONS

A mesoscopic DEM analysis has been performed. In order to present reliable results, a detailed DEM microscopic calibration has been conducted. Once the microscopic numerical parameters are fixed, three dimensional discrete and differently reinforced soil elements have been modelled. The soil elements represent the mesoscopic interaction behaviour between the reinforcement and the surrounding soil structure. The deformation behaviour of the reinforced soil element has been observed in case of utilizing the concepts of PRS_i. Displacements above the geogrid layer have been higher than below the geogrid. The results have shown a sound agreement with respect to the results gained from FEM and PIV analyses. So called arching effects have as reported by Izvolt and Kardos in 2010 become visible. These effects have resulted, in local stress concentrations between the soil particles. The tensile force of the geogrid has distributed constantly along the reinforcement in longitudinal direction. This has been due to the permanent prestress in the longitudinal direction. In the case of utilizing the concept of PRS_i, the transverse members have been strained in the longitudinal direction. The discrete clumps have accessed easily between the single strings.

The conclusion is that the system of PRS_i has been microscopically and numerically validated. As reported by Lackner in 2012, by using the same materials, soil and reinforcement and by prestressing the geogrid reinforcement with the presented concept the load displacement behaviour of reinforced soil structures can be increased steadily.

When the concept of PRS_p is employed, a prestressing trench has been validated as applicable. Experimental studies verify the analytical recommendation for the geometry of the trench.

Finally it can be stated that practical recommendations for the design and construction of PRS_i have been presented. In the near future, design projects will verify the concept and will improve the practical recommendations as stated.

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