The innovative concept of reinforced soil by prestressed geogrids

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ABSTRACT
This paper presents results of numerical and experimental investigations on an innovative construction method for reinforced soil structures by geosynthetics. The concept of prestressed reinforced soil (PRS_i) to improve a reinforced soil structures load displacement behaviour is introduced. Large scale experimental test results produced at the Institute of Soil Mechanics and Foundation Engineering at Graz University of Technology are presented. Over 60 path-controlled static load displacement tests have been performed to investigate the behaviour of ten different reinforced soil structures. In addition numerical simulations based on the Discrete Element Method (DEM) are utilized to calculate and validate the mesoscopic experimental test results. A detailed geometrical discrete modelling of soil particles and geogrid structures has been performed. An innovative method of computer aided design (CAD) for clumps and geogrid structures ensure a mesoscopic modelling of the soil geogrid interaction. The results of the discrete numerical analysis are important not only to validate the experimental results but also to improve and visualize the fundamental understanding of the mechanical behaviour of reinforced and prestressed reinforced soil structures.

1. INTRODUCTION

1.1 General

Different kinds of reinforced soil structures are by now utilized for applications not only in geotechnical engineering. Without the use of geogrid reinforced soil structures many civil engineering projects all around the world would not have succeeded.

1.2 Open Issues

Today the requirements to geogrid reinforced soil structures at least in Austria increase more and more. In comparison to conventional road construction methods, such as bridge abutments, reinforced soil structures sometimes do not behave stiff enough. Developing a system to improve the geogrid reinforced soil structure's load-displacement behaviour is therefore the aim of this research.

1.3 Outline

In order to fulfil the high tech requirements due to the reinforced soil structures, concepts respectively the theory behind the concepts of prestressed reinforced soil (PRS_i) structures are going to be presented consecutively (chapter 2).

To validate those concepts experimental investigations on the innovative idea of PRS_i are going to be presented in chapter 3. Macroscopic results out of 60 large scale load displacement tests at different reinforced soil structures under constant laboratory conditions are summarized.

To validate the concept of PRS_i mesoscopically numerical simulations based on the Discrete Element Method have been utilized and their results are presented in chapter 4. Therefore computer aided designed clumps (CAD clumps) are designed to simulate the soil geogrid interaction accurately. Not only the granular material but also the geogrid reinforcement's geometry is modelled in detail to assure high resolution results.

2. THEORY

2.1 General information

The PRS_i concept's main intent has been to improve the macroscopic load-displacement behaviour of the geogrid reinforced soil structures by increasing the reinforcement's stiffness itself. The load-strain behaviour of some geogrid reinforcements is highly nonlinear, especially in the range of $\varepsilon_{tensile}$ = 0-2%, it is of high importance to stress the geogrid up to a linear high strain level. By increasing the geogrid reinforcement's tensile stiffness the overall system's load displacements behaviour significantly improves.

2.2 Literature Review

The Japanese system of preloaded and prestressed reinforced soil structures (Tatsuoka et al 1997, Shinoda et al 2002) has been developed in 1997. The reinforced soil structure is preloaded respectively prestressed perpendicular to the reinforcement laying itself. Prestressed anchors and concrete plates are mobilized to apply preloading forces due to the reinforced soil structure, mainly bridge abutments.

Lawson et al. (2005) deal with reinforced soil structures, in detail segmental block reinforced soil walls, with constrained reinforced fill zones. In order to constrain the reinforced fill zone the geogrid reinforcement has been connected to anchors which are drilled and fixed into the rock mass. Therefore a considerable amount of geosynthetics reinforcement material could have been saved.

Lovisa et al. (2009) performed laboratory physical model tests and finite element analyses to study the behaviour of a prestressed geotextile reinforced sand bed supporting a loaded circular footing. The investigation's results showed that the implementation of prestress due to the geotextile reinforcement significantly improved the settlement response and load-bearing capacity of the soil.

2.3 Concept

Prestressing the geogrid reinforcement in axial layer direction is the main idea of the concept of PRS_i. By investigating the tensile material properties of most of the geogrids it is visible that their tensile load strain behaviour is highly nonlinear. After compaction on the building site the geogrid is strained and a specific tensile force has been activated but the reinforcement's strain ratio and therefore its tensile stiffness is then unknown.

By prestressing the geogrid reinforcement in a reinforced soil structure with a specific amount the reinforcement's strain and therefore its tensile stiffness is defined. To achieve a prestressing in the geogrid reinforcement the following three different methods have been developed:

- Prestressed reinforced soil by compaction: PRS_c

A prestressing in the geogrid due to compaction of the overfilled granular soil layer (PRS_c) can be achieved by using the spreading stresses σ_{spread} occurring between soil and geogrid interface. Rendulic (1938) described the horizontal and vertical earth pressure distribution on the surface of an embankment with a horizontal base. These loads lead to a spreading of the loosely dumped compaction strip further to a development of lateral stresses on the base of the dumped soil and thereby to an increase of axial forces in the reinforcement layer (Lackner & Semprich 2009).

- Permanently prestressed reinforced soil: PRS_p

Permanently prestressing due to geogrid reinforcements (PRS_p) can be applied by various methods. During the experimental investigations (chapter 4) the axial prestressing in the horizontal geogrid layer has been applied by hydraulic jacks. Mechanically the concept can be compared to a prestressed rope respectively to a membrane structure. The more tension in the geogrid occurs the higher the deviation forces in the vertical direction and the larger is the bedding support provided by the reinforcement. An additional positive effect by prestressing occurs because of the nonlinear load strain behaviour of e.g. PET geogrids. The maximum stiffness of some materials occurs around 1-4 % axial strains ε_{axial}.

- Temporarily prestressed reinforced soil: PRS_t

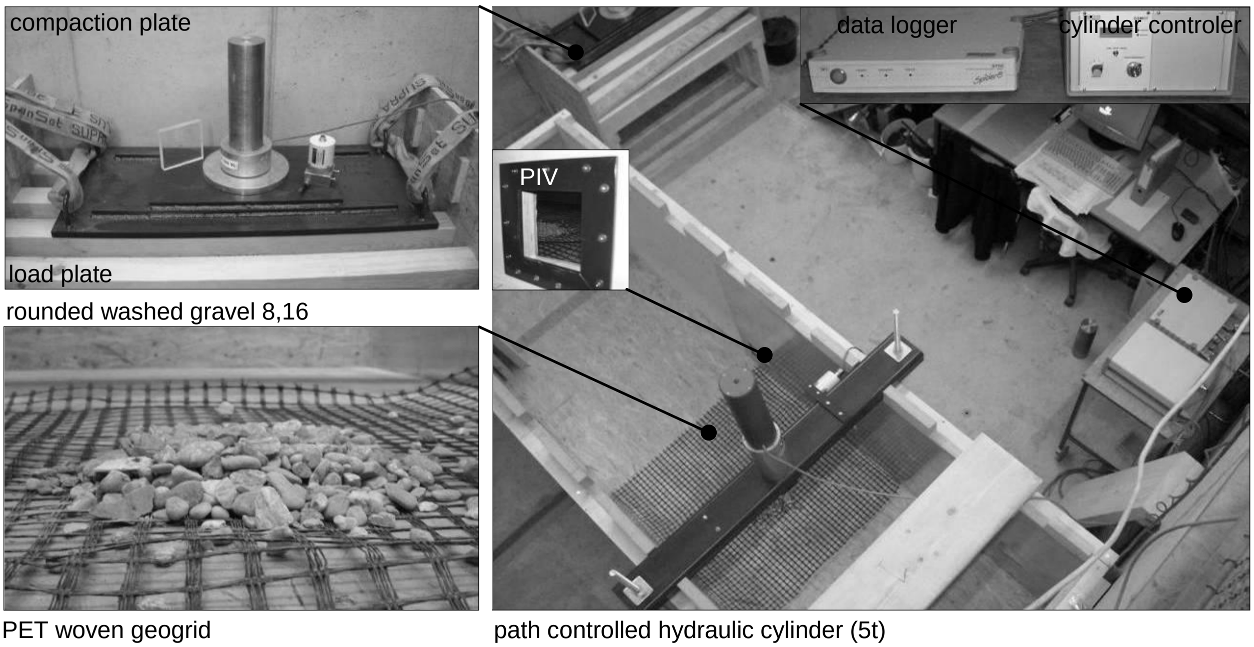
Especially when designing geogrid reinforced structures with coarse grain granular backfill materials temporarily prestressed reinforced soil (PRS_t) is well applicable. By temporarily prestressing the geogrid, its mesh expands and the granular soil particles can easily access the gaps between the polymer longitudinal and transverse members of the reinforcement during the compaction process. After appropriate compaction of the granular soil layer the applied prestressing in the reinforcement is released and by soil geogrid interlocking effects additional pressure forces $F_{contact}$ can be applied to the granular particles.

3. EXPERIMENTAL INVESTIGATIONS

3.1 Experimental setup and testing equipment

To validate the concept of PRS_i the behaviour of ten different reinforced granular soil structures has been investigated in a three meter long, one meter wide and one meter high wooden experimental box surrounded by a mobile steel frame (Brkić 2010). The geogrid reinforced soil structures are built up by three compaction layers, fifteen centimetres each (h_{layer} = 0,15 m), of granular soil and polymer geogrids. Each strip is compacted path controlled with a compaction speed v_{comp} = 2 mm/min until a vertical compaction pressure p_{comp} = 160 kN/m² has been applied. Therefore an computer controlled, electrical hydraulic cylinder with a maximum pressure force F_{max} = 50 kN and a maximum stroke s_{max} = 0,1 m automatically is installed (Figure 1).

Figure 1. Experimental testing device to validate the concept of PRS_i



Computer connected displacement transducers are fixed on the mobile steel beam to measure deformations during the path controlled compaction and during the load testing procedure. The load of the hydraulic jack F_{test} is measured by a full bridge load cell installed between cylinder and the compaction respectively load plate. The prestressing axial to the reinforcement $\varepsilon_{prestress}$ = 2,0 % is applied constantly over the 1 m wide geogrid by a manually handled hydraulic jack.

3.2 Experimental materials

For performing the experimental validation a washed rounded, coarse gravel 8 to 16 mm, C_u = 1,43 typically for Graz, Austria called “Murschotter” is used. The gravel’s unit weight γ_s = 26,4 kN/m³ and the gravel’s natural water content w = 0,21 % has been tested. A maximum porosity of n_{max} = 43,1 % and a minimum porosity n_{min} = 39,0 % have been invested by laboratory studies. A peak friction angle ϕ_{peak} = 40,1 ° is determined by performing large scale direct shear tests. The soils stiffness parameters are investigated by performing stress controlled large scale oedometer tests. The stiffness parameter E = 10-50 MPa has been determined in a stress range of 10 to 100 kN/m².

In order to mesoscopically model (chapter 4) the discrete granular soil particles in detail, investigations relating to the grain geometry have been performed. 150 particles have been selected to perform a detailed geometrical experimental study. Apart from visual classification (von Soos & Bohac) relating to the shape of the grains every particle has been measured with a digital sliding calliper in A (maximum length) B (middle length) and C (minimum length) direction. Thereby a flatness ratio F and a roundness coefficient ψ could have been calculated according to Aschenbrenner (1956). Most of the grains have been analyzed as spherical, oblate biaxial grains. The grain’s sphericity and roundness with respect to a sphere (sphericity = roundness = 1,0) have also been investigated by using the tables provided by Krumbein & Sloss (1963). Further on Rittenhouese (1943) provides a fast method to describe the particle shape’s properties. The results of the analysis are summarized by 4 categories (chapter 4.2) in Table 1.

Geometrical and mechanical biaxial geogrids woven out of linear polyester (PET) are used as reinforcing materials. The geogrids thickness d_{grid} are 1,4 mm and the aperture size $a_{grid,x,y}$ amounts 20,0 mm in longitudinal and 20,0 mm in transverse direction. The interaction coefficient α = 0,95 between granular soil and geogrid reinforcement material has been determined by carrying out large scale direct shear tests.

Table 1: Results out of the mesoscopical grain shape analyse

Shape	Fraction [%]	von Soos & Bohac	Krumbein & Sloss	Rittenhouse
1	43	semispherical / subrounded	sphericity 0,7 / roundness 0,7	subrounded / subangular
2	29	flat / subrounded	sphericity 0,3 / roundness 0,7	subrounded
3	5	spherical / rounded	sphericity 0,9 / roundness 0,9	subrounded
4	23	semispherical / subrounded	sphericity 0,9 / roundness 0,7	subangular / subrounded

3.3 Experimental procedure

First a 0,02 m layer of gravel is dumped at the bottom of the experimental device. On top of the gravel layer the geogrid reinforcement is installed. Compaction strips length/width/height = 0,4/1,0/0,15 m, one by one are dumped and afterwards compacted path controlled to produce a homogeneous soil structure. After installing the first layer (4 strips) a second geogrid reinforcement layer is installed.

As already mentioned the permanent prestressing of the geogrids in the PRS_p structure is applied by a hydraulic jack. Up to a prestressing strain ε_{PRS} = 2,5% the reinforcement is tensioned and permanently fixed after installation.

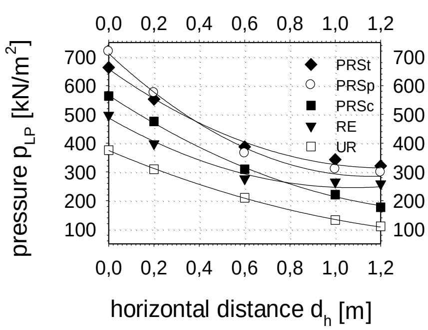
In case of applying prestressing temporarily in the reinforcement the prestrain ε_{PRSp} = 2,5% is slowly released after compaction of each layer in the artificial PRS_t structure.

After the installation of the artificial reinforced soil structure load displacement tests (LDT) at different locations are carried out. Therefore a circular load plate with a diameter B = 0,24 m has been dropped path controlled with a testing speed v_{test} = 5 mm/min until a vertical displacement s = 0,035 m is reached.

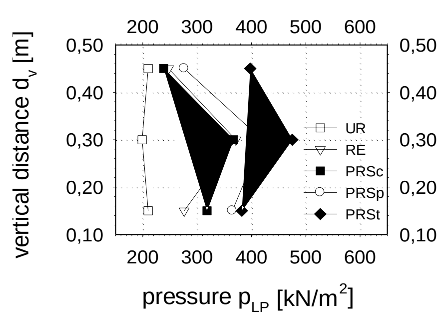
3.4 Macroscopic experimental results and discussion

Macroscopic results of the LD tests are necessary to validate the concept of PRS_i. LD test with different positions, close to far away from the hard facing respectively the soft facing have been performed on different reinforced embankments.

Figure 2. Macroscopic results out of the static load displacement test: a) horizontal pressure distribution along the experimental device. b) vertical pressure distribution along the experimental device.



a) horizontal pressure distribution



b) vertical pressure distribution

The maximum pressures p_{LP} at layer 3 with respect to the same settlement of 35 mm have been plotted from close to the hard facing (0,0 m) to close to the soft facing (1,2 m) and in between (Figure 2a). The pressure distribution p_{LP} at strip 2 (0,6 m) with respect to the height of the artificial soil structure is visualized in Figure 2b. It is visible that the pressure decreases with increasing embankment height. In case of testing the load displacement behaviour just above the bottom of the embankment the influence of the reinforcement on the maximum pressure is small. If the geogrid is not able to deform its activation of strength is quite low.

The results are plotted for different kind of reinforcing concepts. The lowest pressures result out of LD tests performed on unreinforced (UR) soil structures. The pressures increase in case of reinforcing the artificial soil structure conventionally

(RE). The concept of PRS_i leads to a further improvement of the load displacement behaviour. The highest pressures have been activated by reinforcing the soil structure with the concept of PRS_t close to the hard facing.

It can be stated that the concept of prestressed reinforced soil PRS_i has been validated by experimental investigations. By prestressing the reinforcement in the soil structure the overall load displacement behaviour improves significantly.

4. NUMERICAL INVESTIGATIONS

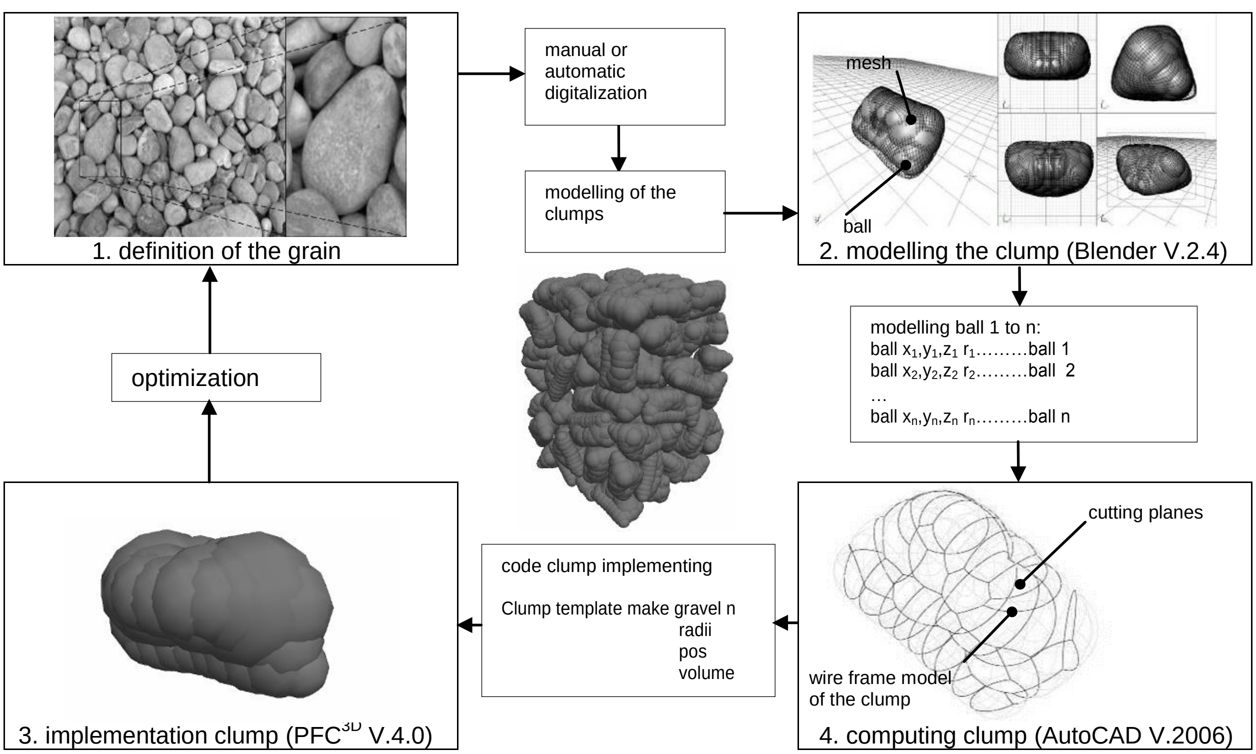
4.1 Numerical setup and testing equipment

The same experimental device as described in chapter 3.1 has been simulated numerically. To gain a detailed in view in the mesostructural load displacement behaviour and the soil geogrid interaction a Discrete Element Method (DEM) simulation has been utilized. Experimental boundaries are modelled by so called walls. The granular material is modelled discretely. Each soil grain is modelled in a first step as a spherical particle and is replaced with a real shaped clump particle consecutively.

4.2 Numerical materials

In order to improve the granular particle interaction behaviour a discrete clump has been visualized as described in figure 3. Additionally an improved contact law, used for granular particles, the Hertz-Mindlin law, has been implemented in the simulation. The input stiffness parameters for this contact law are firstly defined and later calibrated. A shear modulus G = 30 GN/m² and a Poisson ration ν=0,2 have finally been defined. In order to model interfriction processes a microscopic roughness μ = 0,8 is applied.

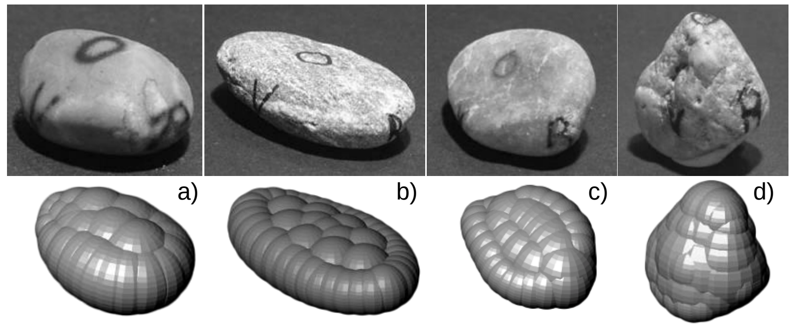
Figure 3. Digitalisation process of a discrete clump: definition – modelling – computing - implementation



In order to describe the granular experimental material by discrete modelling the 4 typical grain shapes (chapter 3.2) have been selected to categorize and consecutively model the shape of the grains numerically by clumps.

Figure 4. Relative fraction particles shape: photo and DEM numerical model of the particles

Particle shape	Fraction	Unit
1	43	[%]
2	29	[%]
3	5	[%]
4	23	[%]



a) … granular particle shape 1
b) … granular particle shape 2
c) … granular particle shape 3
d) … granular particle shape 4

4.3 Numerical procedure

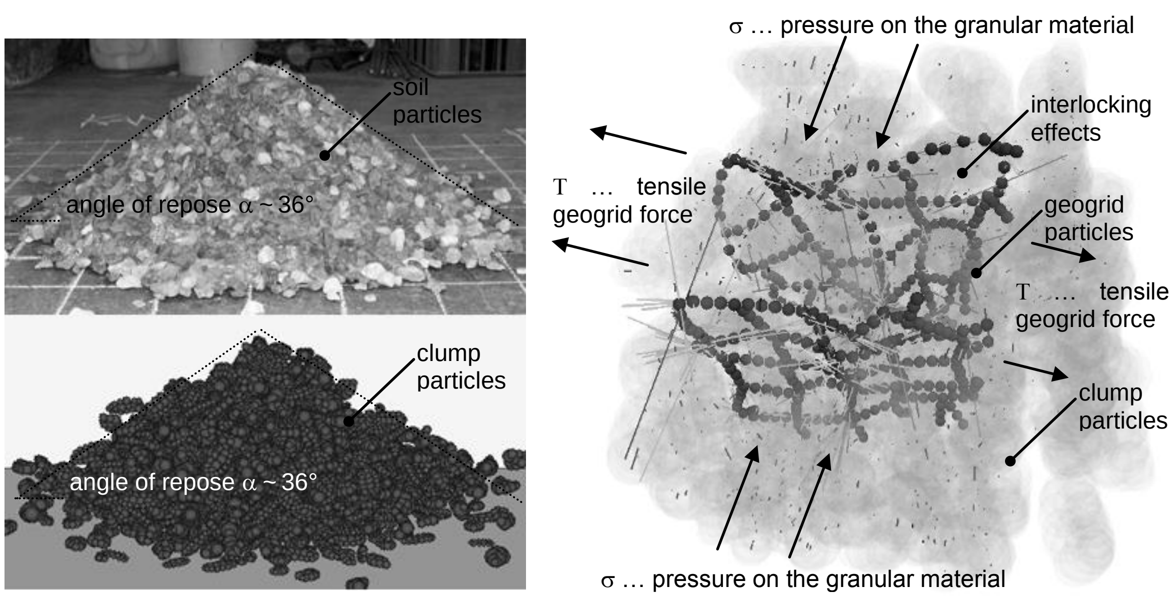
The numerical calculation process can be explained as an explicit dynamic concept. The particle mechanical behaviour is described by the movement of each particle. Newton's law of motion provides the fundamental relationship between particle motion and forces causing motion. In case of a contact between two particles, forces as a result of the contact law act on the moving particles. The calculation process is finished if all particles reach equilibrium.

4.4 Mesoscopic numerical results and discussion

As already mentioned it is essentially important to calibrate the microscopic parameters of soil and geogrid before calculating processes such as the experiment described in chapter 3. For soil calibration element test such as direct shear, triaxial or oedometer test can be performed. But also small scale test such as dumping cones can lead to useful calibration results.

To calibrate the geogrid reinforcement tensile and bending tests have been performed to calibrate the geogrid linear contact model. Normal and parallel bond's strength and stiffness parameters can be calibrated by performing those tests.

Figure 5. DEM mesoscopic calibration results: a) modelling of an angle of repose for soil calibration. b) soil and geogrid calibration by simulating a geogrid reinforced triaxial element test.



a) dumping test
b) triaxial element test

First soil and geogrid have to be calibrated separately. For example the granular particle friction coefficient μ can be numerically defined by performing dumping tests (Figure 5a). Missing parameters should finally be calibrated by tests in which the geogrid reinforcement and the granular coarse grain soil material interact (e.g. triaxial tests, Figure 5b).

The results of the DEM calibration analysis show that the interaction between soil and geogrid can be defined as a interplay of friction- and interlocking effects. On the one hand the soil's tensile stresses occurring during loading can be transferred into the grid by interfriction between surrounding soil and geogrid. An important factor for this interaction is the soil particle's surface roughness and the surface roughness of the geogrid. On the other hand an interlocking effect between the geogrid and the granular soil particles occurs (Figure 4b). Depending on the size and shape of the particle and the mesh size of the geogrid reinforcement these interlocking effects differ.

It can be stated that the soil geogrid interaction can be simulated well by utilizing the innovative concept of CAD clumps. With the help of the described simulation parameter studies referring to the grain size and mesh distance respectively surface roughness's of the geogrid can be performed to quantitatively describe these effects.

5. CONCLUSIONS

This paper has presented numerical and experimental investigations on an innovative construction method for reinforced soil structures by geosynthetics called prestressed reinforced soil (PRS_i). The concept PRS_i to increase the bonded structures load displacement behaviour has been theoretically introduced.

The results of experimental static load displacement tests have been presented. The lowest bearing capacities result of LD tests performed on unreinforced (UR) soil structures close to the soft facing. The capacities increase in case of reinforcing the artificial soil structure conventionally (RE). The concept of PRS_i leads to a further increase of the load displacement behaviour. The highest bearing capacities have been activated close to the hard facing by reinforcing the soil structure with the concept of PRS_t. It can be stated that the concept of prestressed reinforced soil PRS_i has been validated by experimental investigations. By prestressing the reinforcement in the soil structure the overall system behaviour improves.

Further on mesoscopic numerical Discrete Element Method (DEM) simulations have been performed to gain a detailed view in the soil geogrid interaction. It may be stated that the soil geogrid interaction can be simulated well by utilizing the presented innovative concept of CAD clumps. With the help of the described simulation the interaction behaviour of soil and geogrid could have been visualized. It may be concluded that soil and geogrid interact by interfriction and interlocking effects.

6. REFERENCES

Aschenbrenner B.C, 1956. A new method of expressing particle sphericity. J. Sediment. Petrol., 26: 15-31.

Brkić S., 2010. Last-Verformungsversuche am im Labor hergestellten Schüttkörpern. Masterarbeit, Institute of Soil Mechanics and Foundation Engineering, Graz University of Technology. (in german).

Krumbein, W. C., Sloss, L., 1963. Stratigraphy and Sedimentation, 2nd edition, Freeman, San Francisco

Lackner, C., Semprich, S., 2009. A Contribution to pre-stressed reinforced soil. - in: Proceedings of the 4th International Young Geotechnical Engineers Conference. 79 – 82

Lawson, C. R., Yee., T. W. Reinforced Soil Retaining Walls with Constrained Reinforced Fill Zones, Proceedings of the Sessions of the GeoFrontiers 2005 Congress, HASCE, Austin USA,

Lovisa J., Shukla S.K., Sivakugan N., 2009. Behaviour of prestressed geotextile-reinforced sand bed supporting a loaded circular footing. Geotextiles and Geomembranes 28, 23–32.

Rittenhouese, G., 1943. A visual method for estimating two dimensional sphericity. Journal of Sedimentary Petrology, 26: 15-31

Shinoda M., Uchimura T., Tatsuoka F., Tateyama M., Natsuki T. 2002. A new simple method to substantially increase the seismic stability of reinforced soil structures. Soil Dynamics and Earthquake Engineering 22, 1115–1123.

Tatsuoka, F., Tateyama, M., Uchimura, T. and Koseki, J., 1997. Geosynthetic-Reinforced Soil Retaining Walls as Important Permanent Structures, Geosynthetics International, Vol. 4, No. 2, 81-136.

Von Soos, P.; Bohac, J. 2002. Properties of soils and rocks and their laboratory determination. Geotechnical Engineering Handbook, Vol. 1, 119-206. Berlin: Ernst & Sohn.