A contribution to pre-stressed reinforced soil

Une contribution de terre armée précontrainte

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ABSTRACT
In this paper pre-stressed reinforced soil is presented. Two systems are introduced and the recent state of research is commented. A two dimensional plane strain finite element analysis is performed to qualitatively demonstrate the system of constructive pre-stressed reinforced soil. Therefore an example of a typical slope with a geological known sliding plane advanced with a pre-stressed geogrid-anchor combined system is simulated. Furthermore pre-stressing reinforcement as a result of compaction is demonstrated by using a three dimensional discrete element analysis (DEM) with the Particle Flow Code. Qualitatively both systems, constructive pre-stressing and pre-stressed reinforcing as a result of compaction, are numerically analyzed.

RÉSUMÉ
Dans ce document le sol renforcé précontraint est présenté. Deux systèmes sont montrés, et l'état récent des recherches est commenté. Une analyse par éléments finis bidimensionnelle est exécutée pour démontrer qualitativement le système du sol renforcé précontraint constructif. Pour cela un exemple d'une pente typique avec une surface de glissement connu géologique, élargi avec un système combiné de geogrid-ancre précontraint, est simulé. En plus le renfort précontraint en raison de la compression est démontré en utilisant une analyse d'élément discret tridimensionnel (DEM) avec le Particle Flow Code. Finalement les deux systèmes, la précontrainte constructive et le renfort précontraint en raison de la compression, sont numériquement analysés.

Keywords : pre-stress, geosynthetics, slope, reinforcement, compaction, DEM, FEM

1 INTRODUCTION

Since more then 40 years reinforced soil is an important engineering tool for geotechnical problems. Since nearly 20 years geosynthetics as reinforcements are used and these materials are still developing.

In the moment research is in progress to understand the interaction between the reinforcement and the surrounding soil. Several different methods e.g. large scale triaxial tests (Ruiken 2008) or numerical simulations e.g DEM analysis (Zhang et al 2007) are performed to understand and describe the interactive behavior of geosynthetic reinforced soil.

The idea for taking a step forward and pre-stress the reinforcement, generally geogrids, is based on the theory of pre-stressed concrete. The use for pre-stressing the reinforcement is on the one hand defining a special stress level and on the other hand reducing displacements. Defined stress-conditions can be constituted by constructively pre-stress the reinforcement. Therefore several options are possible. For example tensioning the geogrid with the shovel of an excavator (Detert et al 2004) leads to a defined stress level in the geogrid. The current idea for constructive pre-stressing is using a pre-stressed anchorage to create a specific stress state in the geogrid (chapter 2). Beside the idea for constructive pre-stressing the reinforcement pre-stressing by compaction the soil-layers on the geogrid is another possibility. Therefore it is important to elementary understand the interaction of the soil and the geogrid during compaction the reinforced soil layer with a compaction roller (chapter 3).

2 CONSTRUCTIVE PRE-STRESSING

The system to constructively pre-stress a geogrid is based on an already tested nailing of a slope (Herold 2008). In this case the geogrid instead of conventional shotcrete is used to ensure the slope stability. The advantages of this system are, the flexibility to handle topographical unevenness, the ecology minded possibility to vegetate the grid and the economical aspect.

The advanced idea of constructive pre-stressing methods for geogrids is accompanied by the using of a pre-stressed anchorage. With a defined pre-stressed force in the anchor and a specific tensile strength of a geogrid it is possible, depending on the soil stiffness, to calculate respectively define a specific stress state in the soil. In geological known creeping zones respectively failure areas the system advances the effective normal stresses in the failure layer and thereby increases the shear resistance in the gliding plane. By using this system an increase of the slopes stability can be achieved. Figure 1 shows an example of a typical slope with a geological known failure zone.

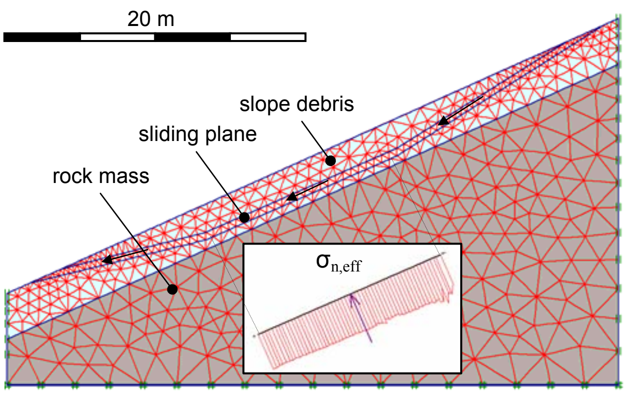

Figure 1. Example of a slope with geological known failure zone.

To qualitatively demonstrate the safety improvement of the above described system an approximately three m thick slope debris laying over an intact rock mass is firstly calculated in a two dimensional plane strain finite element analysis. The slope debris is faulted by an approximately 0.3 m thick geological known failure zone. The global safety factor η is approximately calculated with 1.0 [-]. The value of the maximum effective normal stresses $\sigma_{n,eff}$ in the sliding plane (Figure 1) is about 40 kN/m². In a first run the input sets for all three materials are based on the linear elastic perfect plastic Mohr-Coulomb model.

After installing the combined system of geogrid and pre-stressed anchorage a two dimensional plane strain finite element analysis is performed. A geogrid with a tensile strength of 2000 kN/m and anchors with pre-stress forces of 50 kN/m were implemented to improve the slope stability.

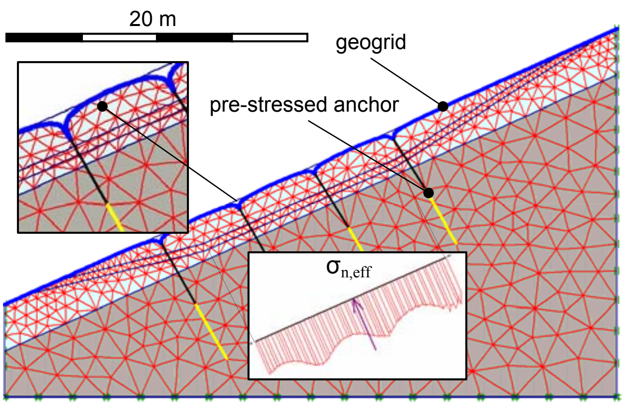

Figure 2. Slope with failure zone improved with geogrid and pre-stressed anchorage.

The maximum effective normal stresses $\sigma_{n,eff}$ in the sliding plane increases up to 55 kN/m² and the global safety of the slope improves (Figure 2).

In active and future research work also three dimensional finite element analyses will be performed. Laboratory tests respectively in-situ tests will be carried out to verify the numerical simulations and to help developing an analytical solution for the described problem. The analytical solution will be leaned on the analytical answer given in the (DGGT AK5.2 2009). A reverse analysis will be performed based on geogrid reinforcement – piles foundations.

3 PRE-STRESSING AS A RESULT OF COMPACTION

A defined pre-stressing in the geogrid because of compaction the overfilled soil layer can be achieved by using the spreading stresses occurring between soil and the geogrid. During compaction static and dynamic loads affect on the reinforced soil. These loads lead to settlements of the loosely dumped soil and thereby to a change of the horizontal stresses.

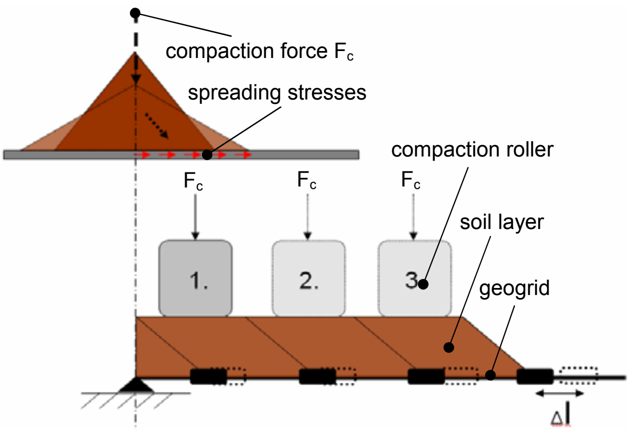

Figure 3. Schematic behavior of pre-stressing as a result of compaction.

On the bottom of the soil, where the geogrid is applied, these forces reach their maximum and because of friction between soil and the reinforcement a tensile force in the geogrid occurs. Figure 3 shows the schematic behavior of the pre-stressing as a result of compaction.

Before dealing with the forces in the geogrid after pre-stressing by compaction and trying to find an analytical solution for this problem research work has to be done. At first the understanding for the interactive behavior between the reinforcing geogrid and the surrounding soil has to be approved.

Therefore a numerical model is applied to show the interaction. For this microscopic scale problem a three dimensional discrete element analysis (DEM) with the Particle Flow Code (Itasca Consulting Group 2005) is performed. The model is made of spherical discrete elements, so called particles, which move independently of one another and interact at defined contacts of the particles. The mechanical behavior of the system is described by the movement of each particle. Newton's law of motion provides the fundamental relationship between particle motion and the forces causing the motion. Where F_j is the resultant force, m_j is the particle's mass and g_j is the body force acceleration vector.

$$\boldsymbol{F}_j = \boldsymbol{m}_j \cdot (\ddot{\boldsymbol{x}}_j - \boldsymbol{g}_j) \quad (1)$$

The rotational motion can be defined with (2) where the M_j is the resultant moment acting on a particle, I_j is the moment of inertia of the particle, ω_j is the angular acceleration and R_j is the particle's radius.

$$\boldsymbol{M}_j = \boldsymbol{I}_j \cdot \dot{\boldsymbol{\omega}}_j = \left(\frac{2}{5} \cdot \boldsymbol{m}_j \cdot \boldsymbol{R}_j^2 \right) \cdot \dot{\boldsymbol{\omega}}_j \quad (2)$$

The numerical model simulates a general system test, where a geogrid is laid on a stiff underground and covered with a layer of soil. To qualitatively demonstrate the system's behavior a biaxial geogrid 1.0 m * 1.0 m is generated with discrete elements.

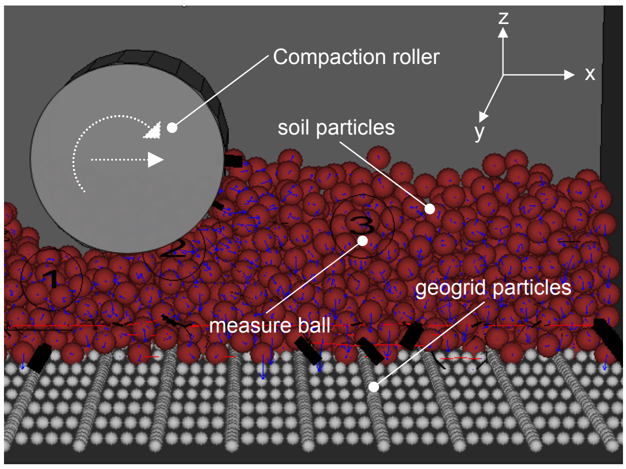

Figure 4. Generated model with the particle flow code.

The radius of the geogrid-particles is 1 cm. The soil is also generated with particles. The radius of the soil-particles amounts 2.0 cm. Figure 4 shows the generated model with the particle flow code.

In a first modeling step a box - out of particle flow intern called walls - is created. Inside this created box the geogrid modeled with particles is laid. The next step includes filling the first 30 cm of the geogrid in y-direction and 1.0 m in x-direction with soil-particles (Figure 4). The height of the soil layer amounts related to a defined porosity of the soil approximately 35 cm. Subsequent the particle flow code calculates all the particles in equilibrium. After reached equilibrium the compaction roller modeled as a cylinder wall rolls over the in filled soil particles. The cylindrical wall moves with a continuous velocity in x direction and a defined spin around the y-axes. The z-position of the compaction roller is related to the defined compaction ratio and is calibrated and controlled on the basis of the soil's porosity after compaction. The soil's porosity is measured and recalibrated by three particle flow code intern called measure balls (Figure 4).

The material parameters of geogrid and soil differ from the input set of the finite element analysis. The particle flow code is based on microscopic parameters. Normal- and shear contact stiffness, k_n and k_s, are used to model the rigidity-properties of the materials. The normal- and shear contact forces are covert by using so called bonds. Parallel bonds with a defined bonding radius are used to model a defined bending capability of a material. The normal and shear contact forces can be expressed as:

$$F_n = k_n U_n \qquad \Delta F_s = -k_s \Delta U_s \tag{3}$$

In (3) the value of U_n is the lapping amount of two separate elements. The ΔU_s is related to the actual velocity of the particles during contacting in a defined time step.

To define the microscopic parameters of the modeled materials several previously calibrations need to be done. For a qualitatively demonstration of the interactive behavior of soil and reinforcement previous researches related to geosynthetics and to granular assemblies (Cundall et al 1979) were adducted to calibrate the model and to run the simulation. In future research work a detailed calibration of each material and the combined system will be performed. Therefore in-situ test with specific geogrids, granular soils and a defined compaction roller are possibilities to calibrate respectively verify the results out of the distinct element analysis.

By modeling the sequence of compaction a detailed insight in the interactive behavior of the geogrid and the overfilled soil can be gained and the general behavior, described in figure 3, can be confirmed. This general understanding helps to develop the idea of pre-stressing the reinforcement as a result of compaction.

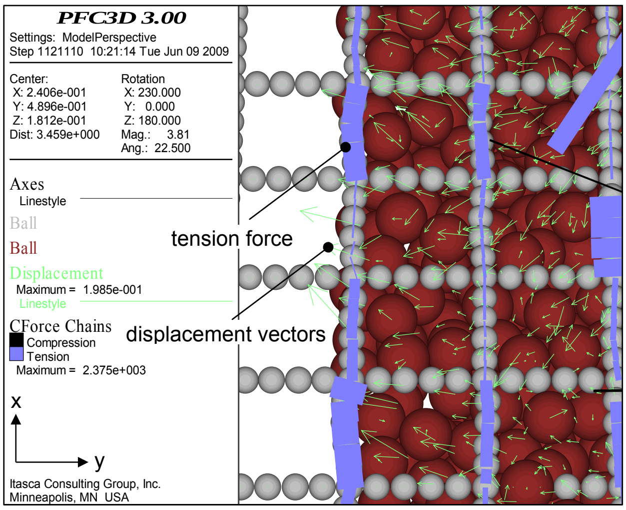

Figure 5. Qualitative trend of pre-stressing the reinforcement during compaction the soil-layer. The thickness of the blue line represents the tensile force in the geogrid string.

The results out of the DEM analysis is the basis for qualitatively confirming the system of pre-stressing the reinforcement by compaction. To describe the factor of compaction the reached porosity in the soil layer is computed over the whole simulation process. In addition the tensile forces in the geogrid, related to the normal contact stiffness oft the reinforcement-particles, are calculated. By drawing the tensile forces in the geogrid vs. the porosity of the soil layer during the compaction a conclusion relating to the pre-stressing of the geogrid as a result of compaction can be given qualitatively.

Figure 5 shows the qualitative results out of the particle flow code analysis. The normal tension forces in the geogrid, calculated by normal bonds between the geogrid-particles occur mainly in x-direction of the reinforcement. In y-direction hardly any tensile forces occur in the geogrid. The reason for that is the missing bearing – the symmetric axes - of the x = 0 reinforcement string in x-direction. For this reason the entire reinforcement, in this simulation, can slide in y-direction. The simulation shows how important the fixing of the first strings of the geogrid before compaction is to generate a defined pre-stressing in the reinforcement. A current simulation is computed where the fixing of the reinforcement's first string is implied.

Meanwhile the compaction modeling with the distinct element simulation is based on a static loading. Relating to the computing time a dynamic compaction might be possible. Therefore the cylinder is going to be accelerated in ± z-direction over the x-axes. However, with the increase of the dynamic load's frequency the computing time increases extensively.

4 CONCLUSIONS

A short overview on pre-stressed reinforced soil was given. Pre-stressing the reinforcement with constructive measures and pre-stressing the geogrid as a result of compaction was presented.

The constructive pre-stressing of the reinforcement was done by pre-stressing the geogrid as a result of a pre-stressed anchorage. Therefore an example of a typical slope with a geological known gliding plane in slope debris laying on an intact rock mass was calculated in a two dimensional plane strain finite element analysis. Qualitatively the analysis showed that the safety of the slope's stability increases by using the described pre-stressed geogrid-anchor system.

In addition a simulation was presented where pre-stressing in the geogrid is implemented as a result of compaction a soil layer on the reinforcement. Therefore a three dimensional discrete element analysis (DEM) with the Particle Flow Code was performed to generally understand the interactive behavior between the reinforcing geogrid and the surrounding soil. Furthermore a qualitatively confirmation of the system's function can be given by plotting the normal forces in the geogrid vs. the porosity of the soil layer during compaction.

5 OUTLOOK

Currently research on the presented topic is proceeding. Advancing the numerical modeling is one of the current and future main goals.

The simulation of the constructive pre-stressed reinforcement will be done with three dimensional finite element analyses by variation of the geogrid properties, the anchor-distance and the slopes geometry.

Especially the calibration of the microscopic material properties, needed for the DEM analysis, is currently in progress to simulate the pre-stressing of the geogrid as a result of compaction. Furthermore the calibrated simulations are going to be computed by variation of the compaction ratio and the material properties of soil layer and reinforcement.

In the future in-situ or laboratory tests should verify the numerical finite and discrete element analysis.

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