THREE-DIMENSIONAL NUMERICAL PARAMETRIC ANALYSIS OF SOIL-GEOSYNTHETIC-INTERACTION

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Abstract: In this paper a FLAC numerical code in three dimensions is used to study the pullout behaviour of geogrids embedded in non-cohesive soils. In a parameter sensitivity analysis, the test-specific and device-specific effects are studied and the main parameters influencing the pullout behaviour of geosynthetics embedded in non-cohesive soils are elaborated.

In order to verify the outcome of the numerical simulations the results were compared to an extensive series of experimental pullout-tests on different geogrid-soil combinations which were carried out beforehand.

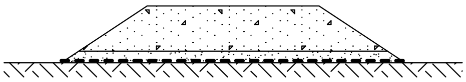
A couple of selected results of the conducted calculation series are presented and discussed. A brief overview concerning the current capabilities to simulate the soil-geosynthetic interaction is also provided.

Keywords: Numerical, interaction, interlock, pull-out test, geogrid.

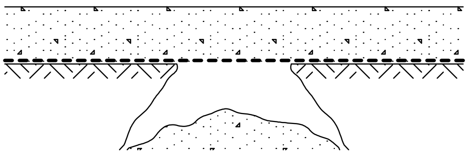
INTRODUCTION

Today geosynthetics are used in a large range of civil and geotechnical engineering applications. Geosynthetics are products such as geotextiles, geogrids, geomembranes etc. They have been used successfully for separation, filtration, draining, reinforcing, protection, sealing and further specific functions for over 30 years. Employing geosynthetics instead of using conventional methods offers significant technical and cost advantages.

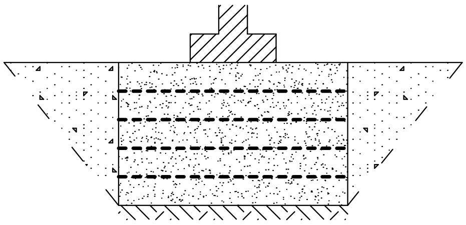
Being economic and ecological, there is a growing global tendency towards geosynthetic use in innovative civil engineering, especially as reinforcing elements in a wide variety of structures. Nowadays it is not uncommon to see their application on reinforced slopes and walls, embankments on soft soils, reinforcement in the base layers of railroad and road constructions, reinforced foundation mattresses, or even the bridging of sinkholes or reinforced abutments (Figure 1).



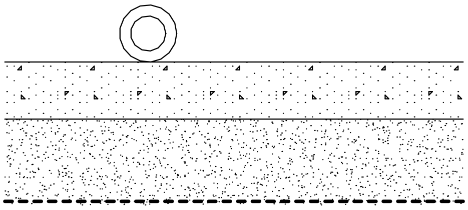
a) Embankments over soft soil



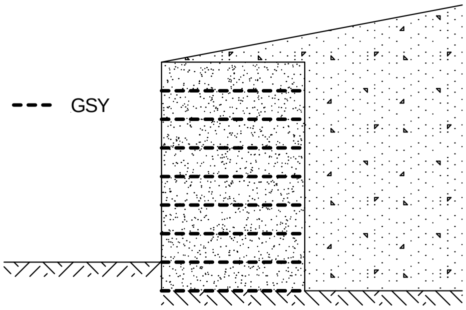
b) Bridging sinkholes or potential voids



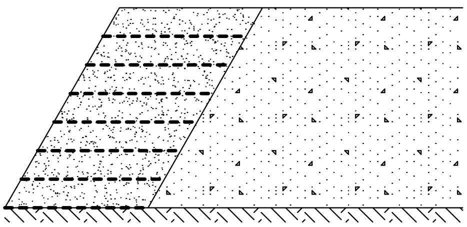
c) Foundation support



d) Soil stabilization and separation



e) Retaining walls



f) Steep slopes

Figure 1. Examples of geosynthetic-reinforced soil (Aydogmus, 2007)

Since the development of soil reinforcement concepts and their application to geosynthetic reinforced structure design, a number of design methods have been proposed, used, and refined. Current practice consists of determining the geometric and reinforcement requirements to prevent internal and external failure using limit equilibrium methods of analysis. External stability involves the overall stability of the stabilized soil mass considered as a whole and is evaluated using slip surfaces outside the stabilized soil mass. Internal stability analysis consists of evaluating potential slip surfaces within the reinforced soil mass. The latter corresponds to failure mechanisms with sliding planes which traverse the geosynthetics. Tension forces in the reinforcement have to be evaluated to guarantee a stable behaviour of the system. The interaction behaviour between soil and geosynthetic is an important key parameter in the design of geosynthetic reinforced structures. The stability of these structures relies to a large extent on the proper transference of forces from the soil to the geosynthetic and vice versa.

The pullout test is the current experimental procedure for determining the interface resistance in cases where the geosynthetic tends to be pulled out of the surrounding soil, even though test results are difficult to interpret and substantially affected by the boundary conditions and other experimental factors.

In order to study the pullout behaviour of geosynthetics embedded in non-cohesive soils and to analyse the complex stress redistribution in and around the reinforcing element a three dimensional numerical analysis with the program system FLAC^{3D} was performed. In a parameter sensitivity analysis, the test-specific and device-specific effects are studied and the main parameters influencing pullout behaviour of geosynthetics embedded in non-cohesive soils are elaborated. The numerical model is verified by an extensive series of experimental pullout-tests on different geosynthetic-soil combinations. In this paper the results obtained are presented and discussed. Beforehand, a brief overview about the current capabilities to simulate the soil-geosynthetic interaction is provided.

NUMERICAL ANALYSIS OF SOIL-GEOSYNTHETIC INTERACTION

The behaviour of geosynthetics including their interaction with the over- and underlying soil is investigated by laboratory and field testing, in-situ measurements, analytical solutions and numerical modelling. Numerical modelling is the most sophisticated and powerful design and dimensioning tool. It allows the calculation of both deformation and stability analysis. More and more, numerical modelling is used in addition to the more classical approaches and step by step some of these approaches will be substituted by numerical modelling. Especially, the necessary consideration of the serviceability limit state (EuroCode) demands the use of numerical modelling. The following provides a general overview of the current capabilities to simulate the soil-geosynthetic interaction (Konietzky, 2006).

Generally, geosynthetic reinforced structures are constructed from the following three elements:

- the soil above and below the geosynthetic,
- the geosynthetic itself and
- the interface between the soil and the geosynthetic.

Each of these elements has to be characterised with mechanical (e.g. stiffness, strength, ...) and hydraulic (e.g. permeability, porosity, ...) parameters through constitutive laws. Initial and boundary conditions (e.g. initial stress state, ground water level, extra loads, ...) should be specified.

The numerical methods available for a calculation of the above mentioned elements can be generally divided into continuum mechanical approaches (e.g. Finite Element Method (FEM), Finite Difference Method (FDM), or Boundary Element Method (BEM)) and discontinuum approaches (e.g. Discrete Element Method (DEM) and Particle Methods). A three-dimensional implementation of the soil-geogrid system is depicted in Figure 2 as an example for each of the approaches.

The discrete element method DEM calculates and simulates discrete, discontinuous procedures, opposed to the classical continuum mechanical approach. The latter modelling depicts the ground as a 3D volume mesh and the geosynthetic as a 2D shell element in between. The interaction is incorporated through interface elements on both sides of the geosynthetic (Figure 2, left hand side). The DEM depicts the soil as discrete elements (particles), and the geogrid as discrete elements which are connected (Figure 2, right hand side). The interaction between geogrid and soil is operated by an automatic contact-algorithm together with special contact-models. Therefore, additional interface elements are not necessary.

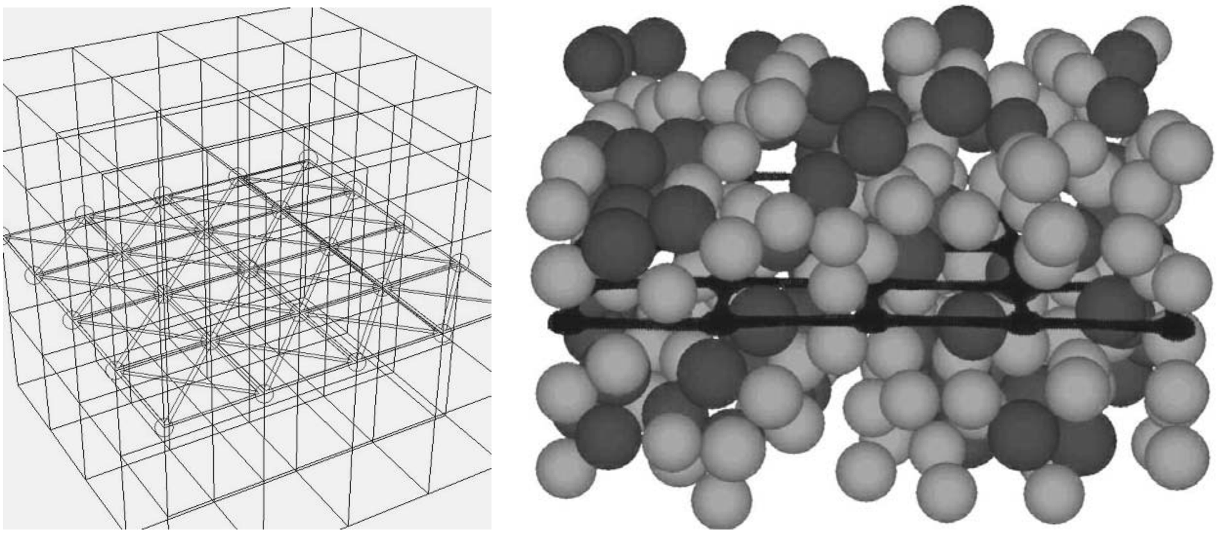


Figure 2. Mechanical continuum (left) and mechanical discontinuum (right) modelling of the soil-geogrid system (Konietzky, 2006)

Apart from the soil and geosynthetic attributes, great importance is placed on soil-geosynthetic interface attributes while modelling. While a geotextile transmits the shear stresses along the surface through friction, geogrid reinforcement additionally interlocks (interlocking effect) with the granular medium.

The mechanism of geogrid-interlocking, although familiar, is a phenomenon still to be investigated. It is a subject matter of today's scientific research.

Figure 3 shows modelling plots of a pullout test in different stages with the programme system PFC (DEM): By pulling the geosynthetic out, mobilised tension forces in the geosynthetic material and stresses in the soil are displayed. The numerical analysis sheds light on the mobilized pull-out force and the level of stress along the reinforcement.

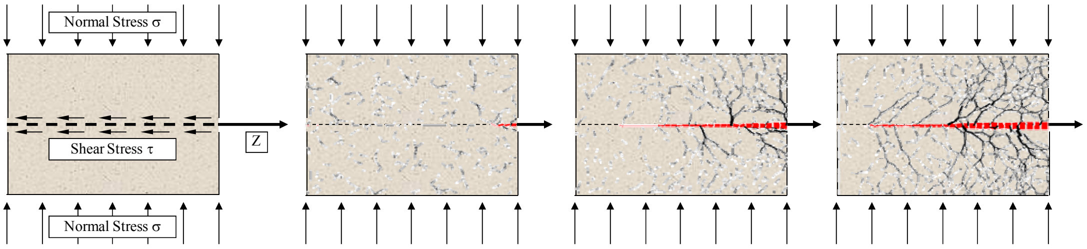


Figure 3. Results of the numerical simulation of a pullout test with the programme system PFC (Aydogmus et al. 2003)

3D MODELLING OF THE PULLOUT TEST OF GEOSYNTHETICS

FLAC^{3D}: Basics of the GEOGRID Structural Element (GSE)

FLAC^{3D} (Fast Lagrangian Analysis of Continua in 3 Dimensions) is a three dimensional explicit finite difference program, used in this study to analyse the pullout behaviour of geosynthetics. FLAC^{3D} incorporates different types of structural elements to model elements such as tunnel liners, piles, sheet piles, cables or rock bolts that interact with the surrounding rock or soil. With version 2.1 a new structural element named GEOGRID has been introduced. GEOGRID Structural Elements (GSE) model shear interaction and the behaviour of flexible membrane support, such as geotextiles or geogrids. The mechanical behaviour of GSE can be divided into the structural response of the geogrid material itself and the way in which the GSE interacts with the FLAC^{3D} grid.

The shear behaviour of the geogrid-soil interface is cohesive and frictional in nature and is controlled by the coupling spring properties of: (k) stiffness per unit area, (c) cohesive strength, (φ) friction angle and by the effective confining stress (σ). The behaviour at the geogrid-soil interface is summarized schematically in Figure 4.

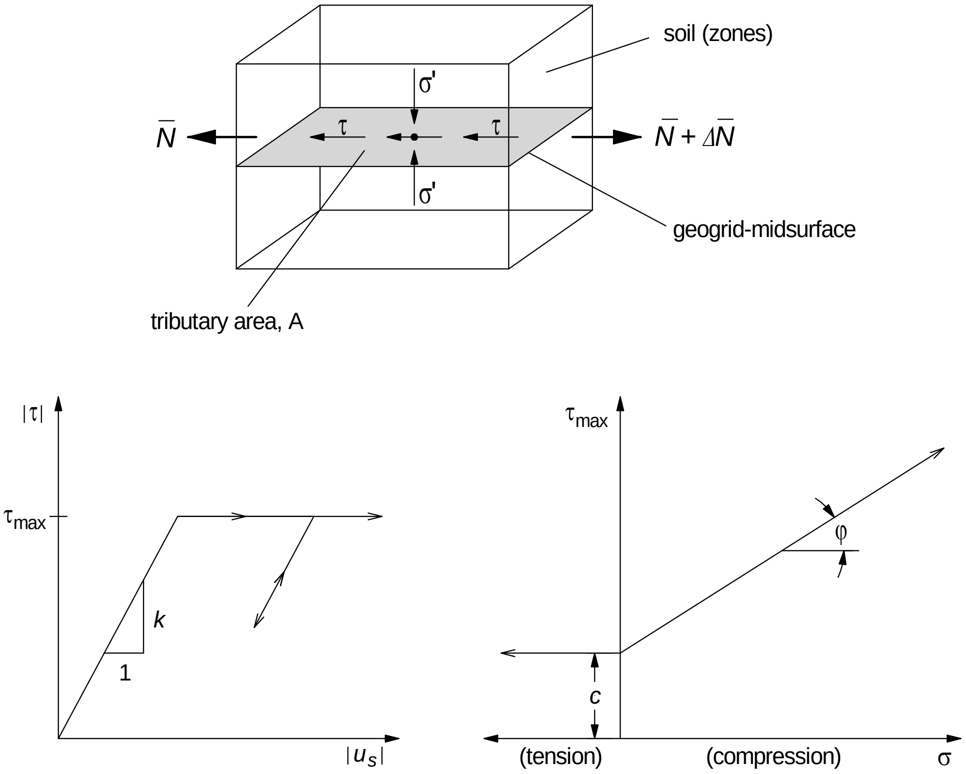


Figure 4. Idealization of interface behaviour of GSE (FLAC3D)

Numerical Model and Material Parameters

The test principle of the pullout test is as follows: A geosynthetic sheet is embedded in a box of soil and then pulled out of the soil, as shown in Figure 5. The pullout force (F) and the displacement (u_i) in different points along the specimen centreline (P_i) are monitored. The test is performed for different values of normal stress (σ).

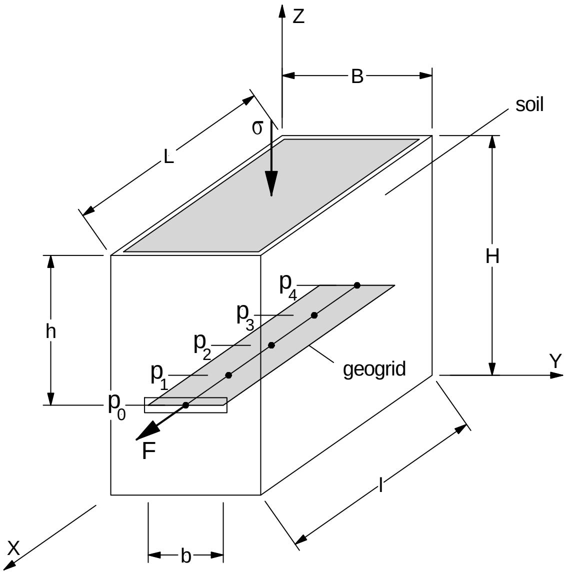


Figure 5. Pullout test configuration

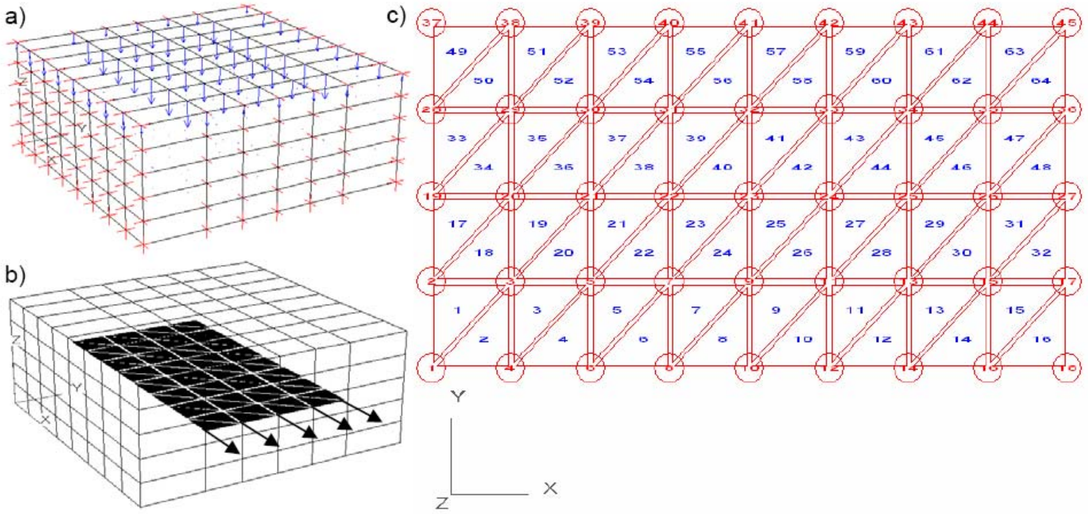


Figure 6. FLAC^{3D} model with: (a) initial boundary condition and surcharge load, (b) geosynthetic sheet and pullout direction, (c) detail of GSE

In order to verify the outcomes of the numerical simulation, the dimensions of the model have been chosen equal to the experimental setup. The pullout testing device is described in Aydogmus et al. (2008) in detail and shows the following dimensions: L=0.5m, B=0.3m, H=0.2m. The test specimen is placed centric (h=H/2) in the soil body and has a width of b=0.25m.

The material model used for the soil is Mohr-Coulomb law. For the geosynthetic a linear elastic material behaviour was assumed. Further it is assumed that failure occurs at the geosynthetic-soil interface. The properties for the reference soil and geosynthetic are summarized in Table 1 and Table 2, respectively. Figure 6 shows details of the established FLAC^{3D} model.

Table 1. Mechanical properties of the reference soil

Parameter	Unit	Value
Elastic modulus E_s	[MN/m^2]	13.5
Poisson's coefficient ν_s	[-]	0.33
Angel of friction φ_s	[°]	38.9
Cohesion c_s	[kN/m^2]	9.4
Angel of dilatancy ψ_s	[°]	9.0

Table 2. Mechanical properties of the reference geosynthetic

Parameter	Unit	Value
Elastic modulus E_g	[GN/m^2]	5.75
Poisson's coefficient ν_g	[-]	0.3
Thickness t_g	[mm]	2.0

Discussion of Selected Results

A couple of selected results of the conducted calculation series will be presented and discussed hereafter. For comprehensive analysis series along with detailed evaluation and discussion refer to Aydogmus (2007).

Validation and verification of numerical models is an important issue in computational geotechnics, thus the mechanical and geometrical parameters of the numerical model are adjusted to the experimental results.

Figure 7 illustrates a comparison between calculated (FLAC^{3D}) and experimental measured results (IPG). The pullout stress versus applied displacement curves for different normal stresses show a good correlation between the data from simulation and from experiment, given the numerical and experimental uncertainties.

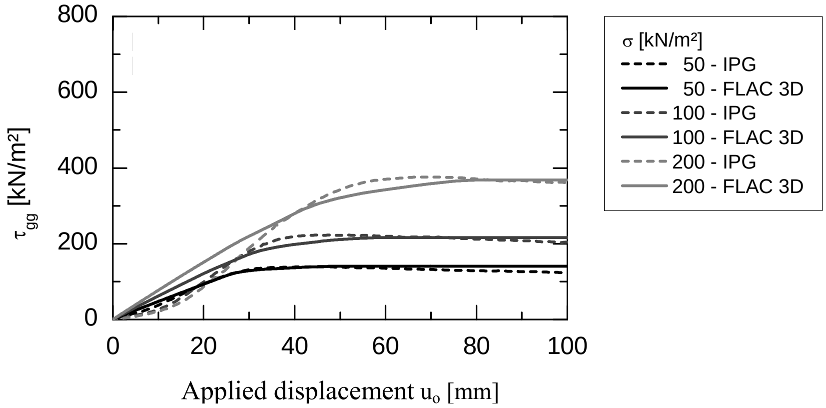


Figure 7. Comparison between experimental (IPG) and numerical results (FLAC^{3D}): Pullout shear stress versus applied displacement

Figure 7 shows the geogrid displacements (u_i) at the locations P_i (from Figure 5) versus the applied displacement u_o over the range from 60 to 80 mm. In this diagram the phenomenon of progressive mobilization of the geogrid as the yielded region progresses inward from the front face can be seen. The equal slopes indicate that all points are moving at the same rate as the front face, and the offsets demonstrate that the front points have moved farther than the back points (also see Figure 9). The very small offset occurs because the geogrid is much stiffer than the surrounding soil such that very little strain develops in the geogrid itself prior to yielding.

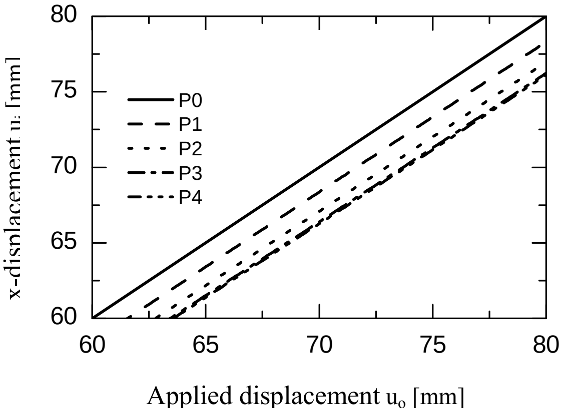


Figure 8. Displacements along geosynthetic centreline versus applied displacement

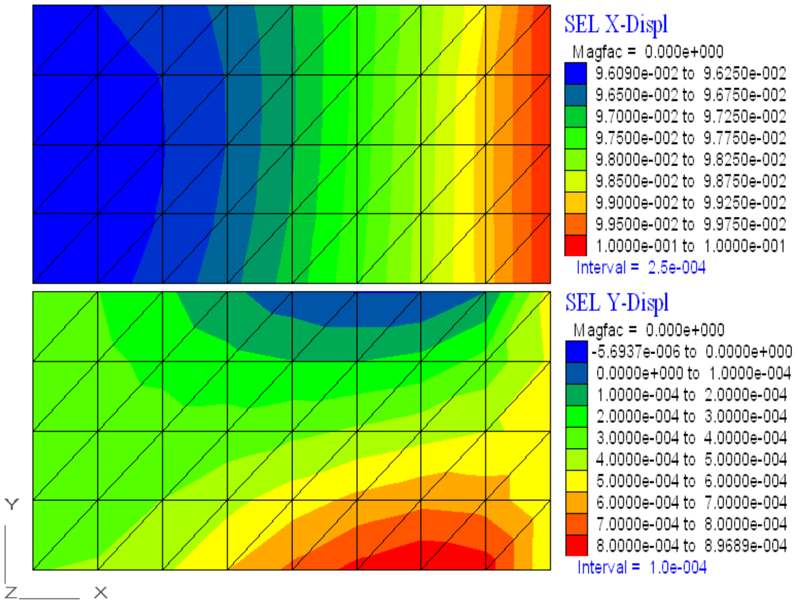


Figure 9. Geogrid displacement field at applied displacement of u_0=100mm

The diagrams in Figure 10 illustrate the influence of the elasticity modulus (E_g) on the activation of the geogrids. The calculations in this series were conducted at identical boundary conditions and with equal material parameters, apart from the elasticity modulus (E_g). The different curve gradients are essentially affected by the activated geogrid shear area and the corresponding transference of forces into the surrounding soil.

The calculated x-displacements u_i along the centreline at the measuring points P_i illustrate that stiffer reinforcement elements are fully activated over the entire embedment length prior to the maximum pullout force F_{max} being reached (Figure 10a). The displacement difference between the front (P_0) and the rearmost point (P_4) is negligible, i.e. the shear stresses acting on the geogrid increase simultaneously in all measuring points. For less stiff geogrids, the movement of the measuring points Pi are in succession, i.e. only partial areas of the reinforcement element are activated (Figure 10d).

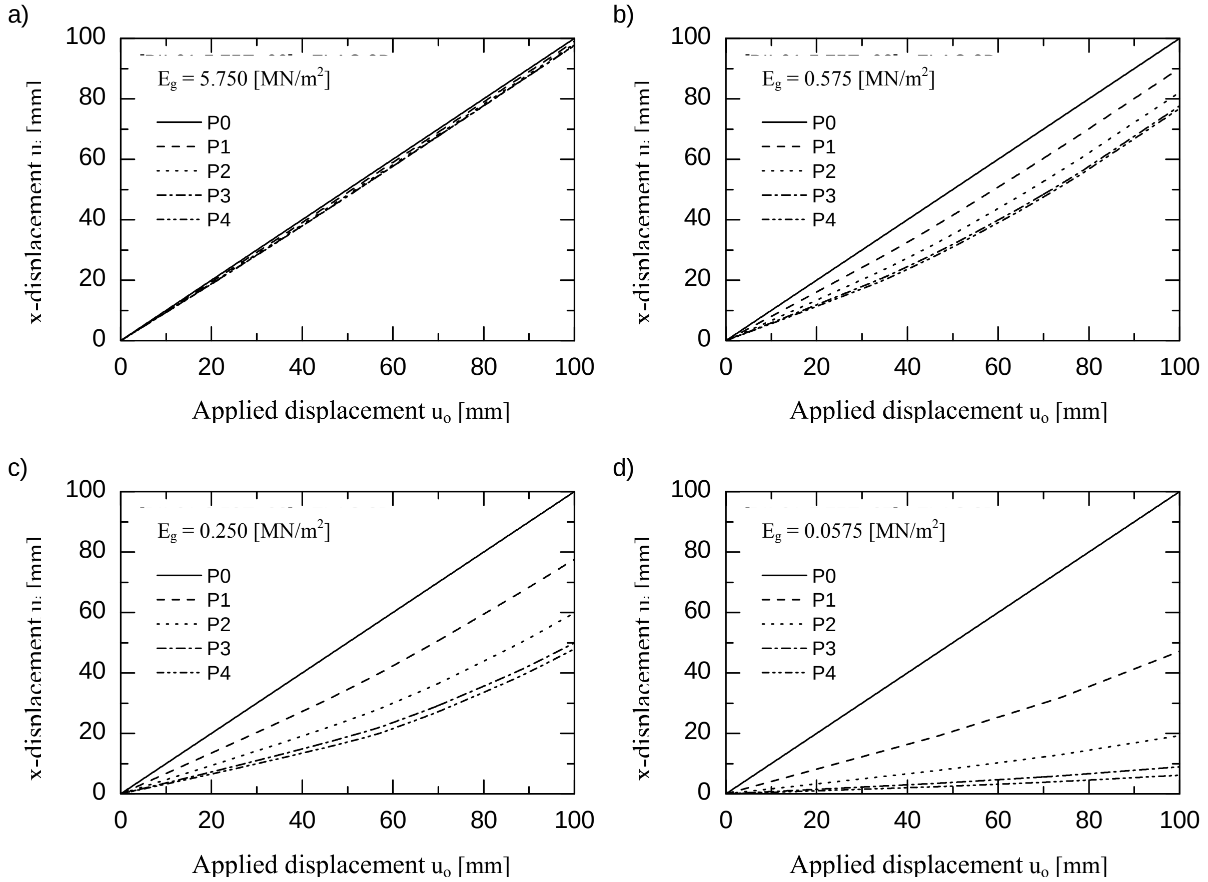


Figure 10. Influence of stiffness modulus on the mobilization of the geogrid

CONCLUSION

In a parameter sensitivity analysis, the test-specific and device-specific effects are studied and the main parameters influencing the pullout behaviour of geosynthetics embedded in non-cohesive soils are elaborated (Aydogmus, 2007). In order to verify the outcomes of the numerical simulations the results were compared to an extensive series of experimental pullout-tests on different geosynthetic-soil combinations which were performed beforehand. The numerical simulations were carried out with the program system FLAC^{3D} under utilization of the GEOGRID Structural Element.

The feasibility of the generated numerical model and the structural element in terms of simulation of pullout tests has been proven. Very complex models involving soil-geosynthetic interaction problems can be solved with relatively little effort and thus these analyses are perfectly practical for daily engineering practice.

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