Investigation of the Soil-Geosynthetic Interaction Using Direct Shear Testing and FEM Method

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Abstract. Verification of the design of the reinforced earth retaining structures is usually based on the global and internal stability check. Beside the analytical solutions, numerical modelling can simulate the real behaviour of the structure including mutual interaction of the particular elements. Additionally, stress-strain relation is involved in the final verification together with the required stability of the system. Parameters such as reinforcement stiffness or interaction ability with the soil allow to calculate more realistic axial forces acting in the reinforcing elements. Analytical solutions don’t take into account the influence of the deformation of the soil mass on the overall and internal stability. Finite Element Method can describe both of these mechanisms which take place simultaneously. Estimation of the interaction parameters is crucial to determine the forces with sufficient accuracy, especially when 2nd limit state is critical for the structure design. The paper is aimed at the laboratory testing and numerical modelling of the interaction of the geosynthetic reinforcement and the soil during the sliding described by the interaction coefficient. A direct shear test was adopted to investigate the actual value of the interaction coefficient which is related to the certain displacement of the reinforcement in the soil. There is a recommendation not to use the interface element at the soil-reinforcement contact when the grid shaped reinforcing elements such as geogrids are used for the numerical simulations. This approach was approved by the study presented in this paper. Reinforcement with the grid structure and rigid joints provides higher level of interaction with the soil environment so reduction of the shear strength at this contact is unrealistic.

1. Introduction
Verification of the design of the reinforced earth retaining structures is usually based on the global and internal stability check. Beside the analytical solutions, numerical model can simulate the real behaviour of the structure including mutual interaction of the particular elements. Additionally, stress-strain relation is involved in the final verification together with the required stability of the system. Parameters such as reinforcement stiffness or interaction ability with the soil allow to calculate more realistic axial forces acting in the reinforcing elements. Monitoring shows some differences in the calculated and the observed reinforcement loads [1]. Analytical solutions don’t take into account the influence of the deformation of the soil mass on the overall and internal stability [2, 3, 4]. Numerical methods can describe both of these mechanisms which take place simultaneously. Estimation of the interaction parameters is crucial to determine the forces with sufficient accuracy, especially when 2nd limit state is
critical for the structural design \[5, 6, 7, 8\]. The paper is aimed at the laboratory testing and numerical modelling of the interaction of the geosynthetic reinforcement and the soil during the sliding described by the interaction coefficient.

A series of laboratory tests using direct shear apparatus and corresponding numerical simulations using Finite Element Method (FEM) was performed to estimate the interaction parameters between geosynthetic specimen and the soil.

2. Geosynthetics for reinforcing

Geosynthetics are products used for installation into the earth structures to enhance, stabilize or protect these structures. Thermoplastic polymers are mainly used for manufacturing of the geosynthetics. Plane geosynthetics such as high strength woven geotextiles, geogrids or geocomposites are usually used as a reinforcing elements. Mechanical strength and interaction of these elements with the soil environment are the main components of the final resistance of the reinforced structure. Two interaction mechanisms take place at the soil-reinforcement contact: friction effect when soil particles are moving and rolling over the reinforcement and the surface friction is mobilized, and racking effect when soil particles wedge into the reinforcement openings, lean against tensile elements and their connections and move together with the reinforcement and the racking resistance is activated. First interaction mechanism occurs on the surface of the flexible geosynthetic reinforcement with rigid tensile elements or connections. Both interaction mechanisms are visible at the rigid geosynthetics such as uniaxial or biaxial extruded geogrids. Effectivity of the geosynthetic is dependent on the structure stiffness, geometry and soil particle-opening size ratio \[6\].

Friction effect can be expressed through the coefficient of the surface friction \(\mu_{gs}\) considering the interaction coefficient \(\alpha'\) at the soil-reinforcement contact related to the \(\tan \varphi_s\), where \(\varphi_s\) is the effective friction angle of the soil \[9\]:

\[
\mu_{gs} = \alpha' \cdot \tan \varphi_s.
\]  

The coefficient \(\alpha'\) can be obtained during the direct shear tests of the geosynthetics and the soil.

2.1. Geosynthetic specimens for testing

The parameters of the selected geosynthetic reinforcements used for testing are in the table 1.

Table 1. Material characteristics of the geosynthetic specimens

| Reinforcement | Model | Tensile strength \(T\) | Axial tensile stiffness \(J\) at break | Units |
|---------------|-------|----------------------|--------------------------------------|-------|
| A – uniaxial flexible polyester geogrid with EVA coating, aperture 25 × 25 mm | Linear elastic perfectly plastic | 60 | 600 |
| B – uniaxial rigid polyester jointed geogrid aperture 50 × 120 mm | | 70 | 1170 kN/m |
| C – biaxial rigid polypropylene geogrid with rigid joints, aperture 65 × 65 mm | | 30 | 330 |

3. Direct shear testing

The testing was performed with the direct shear apparatus with the square box of dimensions of 350×350 mm. The soil specimen consisted of crushed limestone of fraction of 0/32 with the height of 160 mm. Shear box is divided in the horizontal plane to induce the predefined shear plane, thus the soil is divided by this plane. Geosynthetic specimen was placed in the middle of the box between two layers of the soil. One side of the reinforcement was fastened by the clamps to the upper part of the box. During...
the initial confining vertical pressure that corresponded to the test pressure, deformation characteristics of the specimen were estimated by the determination of the soil deformation. Three stages with the normal pressures of 0.125, 0.150 and 0.175 MPa were realized according to the vertical pressure that occurs in the depth from 6 to 9 m bellow the top of the reinforced structure. Bottom part of the box was moving during the test with the velocity of 1 mm/min until the maximum displacement of 100 mm was reached.

4. Numerical model

Numerical model was prepared in the software Plaxis 2D using Finite Element Method. Mohr-Coulomb material model was selected for the soil specimen of crushed limestone (Table 2). The soil parameters were determined during the direct shear test of the plain soil specimen. The cohesion seems to be too high but this is value is apparent cohesion reached in a small box with a rigid walls. This value is valid considering the boundary conditions of the test.

**Table 2.** Material characteristics of the soil specimen

| Parameter             | Name | Value | Units |
|-----------------------|------|-------|-------|
| Unit weight           | γ    | 20.1  | kN/m³ |
| Young’s modulus       | E_ref| 1.8×10⁴ | kN/m² |
| Poisson’s ratio       | ν    | 0.20  | -     |
| Cohesion              | c    | 411   | kN/m² |
| Friction angle        | φ    | 44.2  | °     |
| Dilatancy angle       | ψ    | 14.2  | °     |

Interface elements were placed at the soil-box contact and at the predefined shear plane in the middle of the soil sample (figure 1). Interface elements allow slipping along the interface plane by reduction of the shear strength of the materials via coefficient $R_{inter}$.

![Figure 1. Scheme of the numerical model of the direct shear test](image)

Coulomb criterion describes the limit between elastic and plastic behaviour of the interface where shear strength parameters are reduced to allow slipping along the predefined interface line:

$$\tan \phi_i = R_{inter} \cdot \tan \phi \leq \tan \phi,$$

$$c_i = R_{inter} \cdot c,$$

where:  $\phi_i$ and $c_i$ shear strength parameters for the interface,

$\phi$ and $c$ effective shear strength parameters of the soil.

The parameter $R_{inter}$ depends on the reinforcement and the soil type. Usually, this parameter can be set for geotextiles or membrane type geosynthetics and the value is in an interval 0.5 – 0.9 [10]. For
geogrids, no shear strength reduction is required. Additionally, interface element is applied at the contact of materials of large difference in stiffness or at places where known predefined shear planes occur.

Displacement of the box was simulated by the prescribed displacement, when the maximum value of 10 mm was divided into 10 calculation phases. The $R_{\text{inter}}$ value was iterated for each phase until the shear stress obtained from the laboratory testing was achieved. This approach also takes into account the non-linear behaviour of the soil during the test. The iterated value of the coefficient $R_{\text{inter},i}$ for i-th phase changes the peak friction angle of the soil $\varphi_s$ to actual friction angle $\varphi_{s,i}$ at the soil-soil contact:

$$tg\varphi_{s,i} = R_{\text{inter},i} \cdot tg\varphi_s$$

and to actual friction angle $\varphi_{gs,i}$ at the soil-reinforcement contact as follows:

$$tg\varphi_{gs,i} = R_{\text{inter},i} \cdot tg\varphi_s$$

Interaction coefficient $\alpha'$ at the soil-reinforcement contact from equation (1) for the i-th calculation phase can be expressed as:

$$\alpha'_i = \frac{tg\varphi_{gs,i}}{tg\varphi_{s,i}}$$

5. Results and discussions
Iterated $R_{\text{inter}}$ values for particular direct shear test related to the shear box displacement are plotted in figure 2.

![Figure 2. Iterated $R_{\text{inter}}$ values for the FEM model](image)

Displacement-shear stress dependency shows typical propagation for the soil with unit weight $\rho_d \geq 1700 \text{ kg/m}^3$ [11]. Noticeable peak related to the peak shear strength with the following decrease can be clearly seen (figure 3). Added reinforcement significantly influences the shear stress path. Despite the flexible structure, specimen A is able to stabilize the fill grains what leads to the increase of the shear resistance. Specimen C accumulates the shear stress in almost same amount as the specimen A despite the lower tensile stiffness. This is possible because of high stiffness of rigid monolithic joints. On the contrary, specimen B with the highest tensile stiffness shows drop of the shear resistance which is caused by the disruption of the bonded structure of the reinforcement. Presented results confirm the stabilization contribution of the geosynthetic reinforcements with rigid joints in opposite to the bonded or yielding connections.
Non-linear development of the interaction coefficient $\alpha'$ takes place during the shift of the box (figure 4). Tensile and structural stiffness influence the level of interaction. Flexible reinforcement (specimen A) reaches markedly smaller values in comparison with the stiffer reinforcement. Higher axial tensile stiffness allows to reach larger values of the interaction coefficient (specimen B) but bonded structure leads to drop as same as at the specimen C while the monotonous development after the peak value was reached with the flexible reinforcement (specimen A). Interaction coefficient oscillates around the 1.0 for the specimen B and C what means that the shear strength at the soil-reinforcement contact is not...
affected considering the equation (1). On the other hand, flexible specimen A decreases the $\tau_{\phi s}$, what means that this type of the reinforcement acts as an imperfection in the soil mass.

![Graph showing interaction coefficient $\alpha'$ at the normal stress 0.125 MPa](image)

**Figure 4.** Interaction coefficient $\alpha'$ at the normal stress 0.125 MPa

6. Conclusions

Actual value of the interaction coefficient depends on the box displacement when small values are observed at small displacement. A certain shift of the box is required to fully activate the soil-reinforcement interaction potential but this displacement should not have the destabilization effect for the retaining structure.

Maximum values of the interaction coefficient are reached after the peak shear stress with the exception of the specimen B with the highest tensile stiffness where the maximum values of both of the quantities coincide. Considering the use of the peak shear strength parameters for the retaining structure design, the interaction coefficient related to the peak shear strength should be used. Values from this interval vary from 0.8 to 1.0 which is in good agreement with the standards and technical papers of geosynthetic manufacturers [9]. There is a recommendation not to use the interface element at the soil-reinforcement contact when the grid shaped reinforcing elements such as geogrids are used for the numerical simulations. This approach was approved by the study presented in this paper. Reinforcement with the grid structure and rigid joints provides higher level of interaction with the soil environment so reduction of the shear strength at this contact is unrealistic.

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