RELEVANT PROPERTIES FOR REINFORCING PRODUCTS BASED ON LATEST RESEARCH AND FIELD MEASUREMENTS

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ABSTRACT

The application of geotextiles as soil reinforcement in roads, embankments and inclined to vertical earth wall constructions has proven a valid and very beneficial technique in the last decades. Many different products are available on the market, such as grids or wovens, made from different raw materials and also different production technologies. Application engineers and customer are sometimes confused about the relevant properties and sufficient design parameters due to the amount of research and publications carried out worldwide. This research aims to summarize and explain the relevant properties of geotextile and provide the application engineers and customers with a guidance how to implement those information in their design approach and it consequences are discussed. For instance, it is well known that parameters such as surface hardness and roughness and geometry of a reinforcement product dominates the interaction behaviour between soil and reinforcement. Depending on the product, the interaction may occur based on friction, interlocking and or the mobilisation of soil strength and passive earth pressure. However, for design purpose only the coefficient of interaction as a result of all resistance components is considered whereas achievement of the expected interaction level is considered in design stage. In this research, these parameters and tensile and/or bending stiffness, will be discussed for general applications for a reinforced retaining wall application based on finite element and limit equilibrium analyses. Finally, the recommendation on the appropriate selection of reinforcement are provided and its influence on the required design tensile strength are discussed.

1. INTRODUCTION

Construction of reinforced retaining walls by geosynthetics has become a popular technique since its first introduction in the 1970's. The proper estimation of reinforcement and backfill material strengths is one of the most challenging topics in the design of such reinforced walls. There always have been a long discussion on proper calculation of required resistance forced to achieve the internal stability, while this required resistance force should be in balance with the available one. The required force for internal stability depends on the geometry of the system, external forces, and the type of the material used in construction. When the retaining wall is reinforced, the reinforcements will also contribute in transferring loads on top of available soil resistance component. Several researchers illustrated the dependency of the mobilized tensile strength of reinforcement on the strain level in the reinforcement and soil. Jewell (1985) found that the required and available forces vary with the level of mobilized strain in backfill and

reinforcements. Therefore, a sustainable internal equilibrium for an optimized design requires the compatibility of the required force with the available resistance (mobilized shearing resistance in soil and tensile strength in reinforcement) at working strain level. Consequently, Jewell (1996) showed that an adequate design of the reinforced wall should ensure that the design values chosen for the reinforcement and the shear strength of backfill material are mobilized together whereas the equilibrium is guaranteed with acceptable deformation in the structure.

In last decades, several manufacturing techniques and raw materials are used to produce reinforcements with distinct mechanical and physical properties. These products have a wide range of axial and bending stiffnesses as well as tensile strengths that can be relevantly used for different applications. There are several applications where different types of reinforcements with particular mechanical and physical properties can be applied. However, the interaction between the reinforcing components and the soil in almost all applications is specified with respect to the mobilization of strain and strength in the soils and reinforcements. Accordingly, the general concept of appropriate determination of mobilized strength of soil/reinforcement should be accommodated for almost all applications in reinforced soil field. Despite of the importance of balancing the mobilization of the strengths in soil and reinforcement by the use of geotextiles with relevant stiffness and sufficient tensile strength, there are some applications where using extremely stiff reinforcement guarantees better performance of the system (e.g. sinkholes and embankments with basal reinforcement). However, for other applications (e.g. footings, roads, retaining walls, embankments, encased columns, etc.), the influence of axial and bending stiffnesses on the system behavior, interaction between reinforcement and its surrounding material, stability, and forces develop in geotextile should be precisely considered.

Lackner (2012) investigated the interactions between soil and geogrid in mesoscopic scale. He reported three main interaction components are activated in soil-geotextile contact, namely (i) frictional interaction between the soil particles and the surface of the geogrid, (ii) interlocking the soil particles between the discrete members of the geogrid, (iii) the alignment effect. The third component deals with aligning the reinforcement around the soil particles which results in higher horizontal and vertical resistances due to deviation of the axial tensile force. Therefore, for reinforcements with high bending stiffness, the 3rd resistance component (alignment effect) will be omitted. The resistance components and their relation with the 3 dimensional deformations in geogrids are schematically shown in Figure 1. As the consequence of the experiments conducted by Lackner (2012), bonding flexibility of geotextiles can provide better interactions between soil and reinforcement while all three resistance components can be fully activated.

Lees (2014) experimentally measured the influence of confining on soil-geogrid interactions. This research showed that at 1 cm above the geogrid did both friction angle and cohesion reduce, possibly due to a lower density of soil immediately around the geogrid. This lower density has been interpreted by the insufficient compaction around the geogrid due to higher energy absorption by geotextiles with bending stiffness. However, by the use of reinforcements with high bonding flexibility, the compaction energy will be completely transferred to the soil while bonding flexibility permits compact arrangement soil particles around the aligned geotextile which forms a dense region around the reinforcement. In contrast, low alignment characteristics of geotextiles with bending stiffness restricts the compaction of the soil that can result in weak interaction between soil and geotextile.

Fakher rand Jones (2001) numerically investigated the influence of bending stiffness of geogrid on the bearing capacity of a footing on reinforced soft clay with high water content. They revealed that the bending stiffness of reinforcement is not important when the underlying clay is not in a super soft state. However, this research conducted by Fakher and Jones (2001) does not deal with the poor compaction of soil in the vicinity of reinforcement with high bending stiffness (Lees 2014) and does not account for elimination of resistant component due to alignment effect (Lackner 2012). With reference to the aforementioned research, it seems that the bending stiffness or reinforcement does not particularly improve the mechanical behavior of reinforced soil in most of the geotechnical applications (e.g. retaining walls, footings, embankments, etc.) but also weaken the interactions between soil and reinforcement that can result in lower resistance. Therefore, this paper aims at assessing the influence of the tensile stiffness on the behavior of reinforced soils.
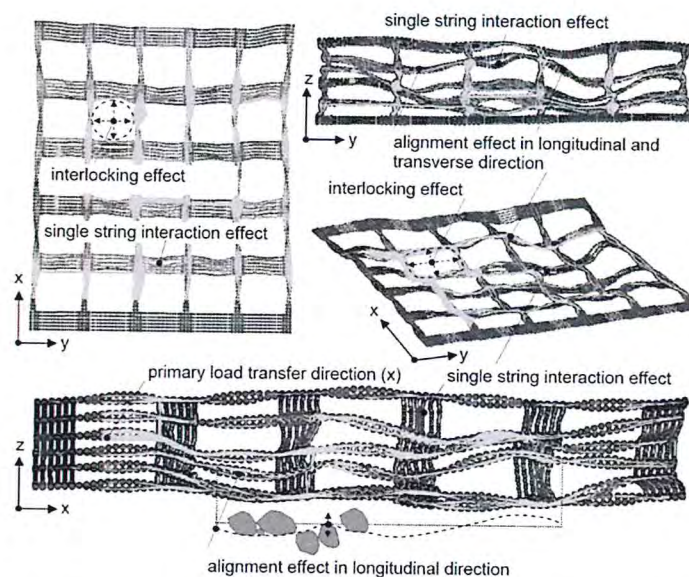
Figure 1. The deformation of geogrid due to different resistance components in mesoscopic scale
(Lockner, 2012)

Rowe and Ho (1997) revealed that the total force required for internal equilibrium of a reinforced soil wall is mainly dependent on the friction angle of backfill material while its other mechanical properties play no significant role in determination of available resistance force. Helwany et al. (1999) illustrated that the performance of reinforced soil wall systems is mostly sensitive to the mechanical properties and physical type of the backfill material. Ling and Leshchinsky (2003) reported higher lateral displacements and reinforcement strains in walls built with weaker granular backfills. Hatami and Bathurst (2006) have interrelated the weakness of the backfill to smaller friction angle value. However, regarding the concept of the strain dependency of the available and required forces (Jewell, 1996), the stiffness of the backfill material should play a remarkable role in achieving the equilibrium and therefore the system behavior of the reinforced walls. Thus, this paper, focuses on the system behavior for a reinforced wall by having a detailed insight into the mobilization of the shear strength in backfill soil and tensile strength in reinforcement as well as the forces develop in reinforcement for different cases. To achieve these objectives, a wrap-around

reinforced wall with a fixed geometry with variable stiffness of backfill soil and reinforcement is numerically simulated and the obtained results are discussed.

2.   NUMERICAL SIMULATION PROCESS

In this research, a reinforced wall with wrap-around facing having the height of 6 m has been taken into consideration. Regarding the recommendations made by EBGEO (2011), the length of the reinforcement layers are defined to be 4.2 m (70% of wall's height). The anchorage length of the reinforcement layers is assumed to be 1.5 m. The height of wrap-around steps is taken 0.5 m which also refers to the thickness of each backfilling step in staged construction. To consider the effect of variation of stress distribution and also deformations in the reinforcement due to construction, the stages of construction have been numerically simulated by adding one wrap-around step with the thickness of 50 cm in each phase of construction. At the end of construction phases, a constant surcharge of 25 kPa with the length of 7 m is vertically applied on the top of backfill. The schematic shape of the reinforced wall is shown in Figure 2.
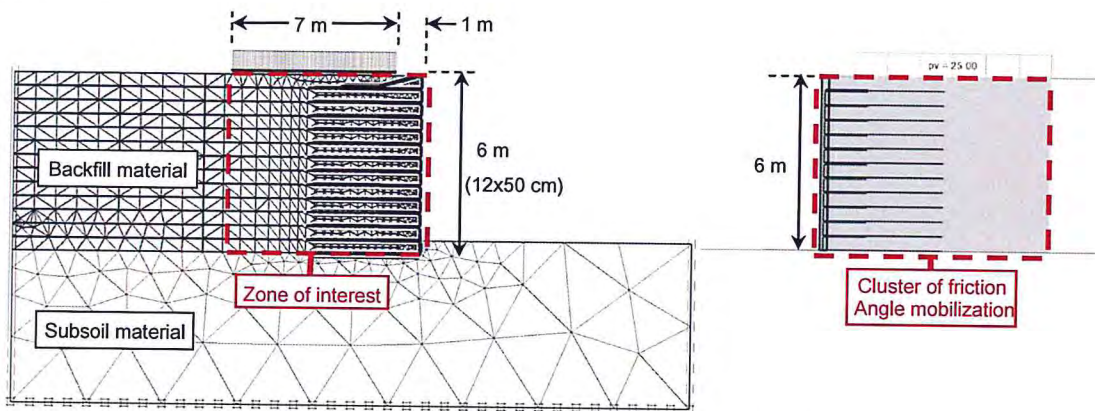

Figure 2. Schematic shape of the wrap-around retaining wall in present study
(Right: GGU-stability model; Left: FEM model)

In these analyses, 3 different materials namely backfill, subsoil and reinforcement are taken into consideration. The physical properties of the materials are shown in the following Table 1.

Table 1. Parameters of the material in this study

Properties Material	$E_{oed.}^{ref}$ (MPa)	E_{50}^{ref} (MPa)	E_{ur}^{ref} (MPa)	m	c (kPa)	ϕ (deg)	ψ (deg)	R_{int}	γ_{unsat} (kN/m³)	γ_{sat} (kN/m³)
Filling Soil (HS model)	25~100	$E_{oed.}^{ref}$	$3E_{oed.}^{ref}$	0.5	1	35	5	1.0	18	19
Base (Linear elastic)			E=800 MPa					1.0	17	18
Reinforcement			EA= 500~2,000 kN/m							

In the numerical analyses, the mechanical behavior of the filling soil is simulated by the use of Hardening Soil (HS) model (Schanz et al., 1999), while the semi-rigid base soil and the reinforcement material obey linear elastic model. In HS model, the stiffness of the material is defined based on secant stiffness for primary loading (E_{50}), stiffness of primary oedometer loading (E_{oed}.) and unloading/reloading stiffness (E_{ur}). The shear strength of the material is determined with reference to friction angle (ϕ) and cohesion (c). The dilation angle of soil (ψ) controls shear dilatancy and m states the power for stress-level dependency of stiffness. Furthermore, γ_{unsat} and γ_{sat} show the soil unit weight at wet and saturated conditions. A perfect interaction between backfill material and reinforcement layers have been assumed by taking strength redaction factors (R_{int}) equal to 1.0.

According to classic soil mechanics, the stiffness of the porous material depends on the size and shape of the particles as well as its relative density (or degree of the compaction). Different researchers have assumed different values for the granular materials compacted with different techniques (Filz et al., 2000; Huang et al., 2009). Huang et al. (2009) simulated two reinforced walls with well-constructed backfill that is carefully compacted by different compactors namely rammer-type and vibrating plate compactors. They assigned the stiffness of 80 MPa to a clean washed granular sand that is backfilled in layer with the height of 15 cm and carefully compacted with heavy electromechanical vibrating rammer compactor under fully controlled condition in lab. Therefore, this stiffness can refer to an extremely perfect backfilling material that is well constructed under careful condition. To the knowledge of the authors, a range of 25 to 100 MPa is the possible stiffness for practical backfills at construction sites. Therefore, this research has focuses on this range to study the influence of backfill stiffness variation on the system's response. Regarding the axial stiffness of reinforcing material, a wide range of EA= 500~2000 kN/m has been assumed.

3. RESULTS AND DISCUSSIONS

Stress/strain mobilization in soil

As mentioned before, Jewell (1985) indicated that the available resistance forces of backfill and reinforcement depend to a large extent on the mobilization of shear strength. Afterwards, Yang et al. (2010) studied the mobilization of reinforcement tension within geosynthetics reinforced structures. They manifested that despite of assuming full mobilization of the tensile resistance of reinforcements in most of design approaches based on stability analysis, the percentage of tensile force mobilization is function of shear strength mobilized in soil that depend on the strain level (deformation) in soil. The results obtained by Yang et al. (2010) are in a total consistence with the concept formerly provided by Jewell (1995, 1996). This is also well proven by a number of lab and field measurements carried out by Arriaga (2003). These measurements also indicated a non-uniform mobilization of the tensile force over the length of the reinforcements. The numerical simulation of two large-scaled GRS retaining walls by Yang et al. (2010) revealed that the mobilization of the tensile capacity of the reinforcements is achieved when more than 95% of shear strength of the soil in their vicinity is mobilized. Regarding the difference between shear strain corresponding to full mobilization of shear strength of soil and the maximum tensile capacity of reinforcement, existing experimental and numerical studies indicate that less than 30% of reinforcement strength is mobilized when the average mobilized soil shear strength reaches peak soil shear capacity (Yang et al., 2010). However, this percentage of reinforcement strength mobilization strongly depends on the type and characteristic properties of its surrounding soil and the

surcharge pressure. For looser soils with more flexible behavior (peak shear strength at higher strain), the higher ratio of tensile capacity of reinforcement will be mobilized at the full mobilization of soil strength, while for stiffer soil this will be less. Therefore, in addition to investigating the deformability of the reinforced wall system, this research aims at evaluating the influence axial stiffness of grid and stiffness of backfilling soil on the stress-strain distribution in the soil and the magnitude of the force develop in the reinforcement layers. The variations of the shear strain in the retaining wall soil for different backfilling stiffness are shown in Figures 4 and 5 for reinforcing material with low and high tensile stiffnesses, respectively.
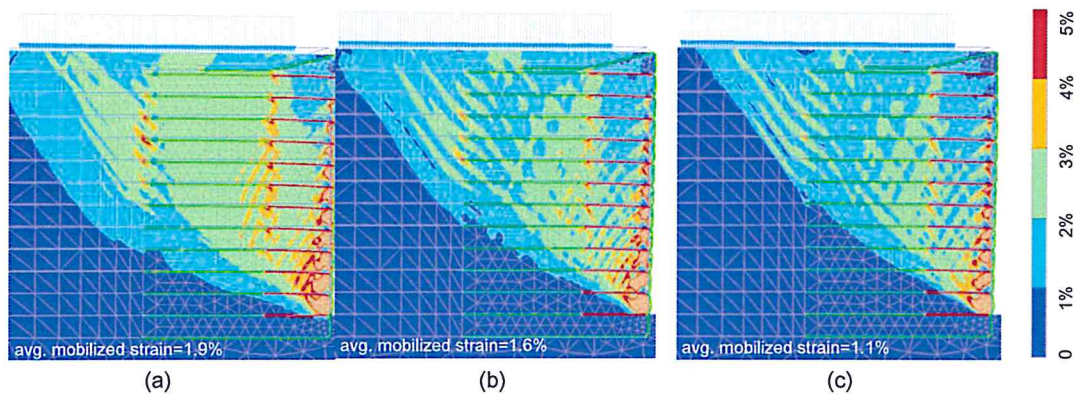

Figure 4. Mobilized shear strain in backfill reinforced with reinforcement having low stiffness EA=500 kN/m; (a) $E_{oed.}$= 25 MPa [ε_{peak}=5.6%], (b) $E_{oed.}$= 50 MPa [ε_{peak}=2.9%], (c) $E_{oed.}$= 100 MPa [ε_{peak}=1.4%]
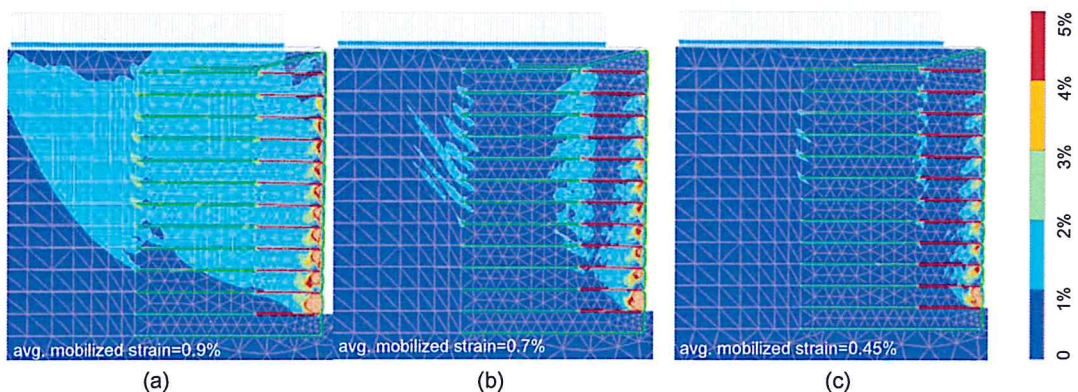

Figure 5. Mobilized shear strain in the backfill reinforced with stiff reinforcement EA=2,000 kN/m; (a) $E_{oed.}$= 25 MPa [ε_{peak}=5.6%], (b) $E_{oed.}$= 50 MPa [ε_{peak}=2.9%], (c) $E_{oed.}$= 100 MPa [ε_{peak}=1.4%]

As seen in Figure 4(a), when soil with lower stiffness ($E_{oed.}$=25 MPa) is used for backfilling, the average shear strain mobilized in the zone of interest (shown with dashed line in Figure 2) is about 1.9%. Accordingly, if just reinforced zone was considered, higher values for average mobilized strain would be obtained. To practically estimate the level mobilization of shear strength for each case, the results of a numerical simulation of triaxial test on the backfilling materials used in this study are shown in Figure 6. As seen in Figure 6, the full mobilization of the shear strength occurs at peak strain (ε_{peak}) equal to 5.6%, 2.9%, 1.9%,1.4% for $E_{oed.}$=25, 50, 75, 100 MPa, respectively. Comparing

peak and mobilized strains in Figures 4 and 6 shows that more than 95% of shear strength has been mobilized in the backfill that is reinforced with geotextile with lower stiffness (EA=500). By a back calculation, the average mobilized friction angle $\varphi_{mob}=(\varepsilon_{mob}/\varepsilon_{peak})\times\varphi_{max}$ in soil body is about 29°, 33° and 34° for $E_{oed.}$=25, 50, and 100 MPa, respectively. However, by using stiffer reirforcements (EA=2000), the average mobilized shear strain in loaded domain is approximately equal to 0.9%, 0.7%, and 0.45% whereas, these strains correspond to the average mobilized friction angle of φ_{mob}=22°, 26°, and 27° respectively for $E_{oed.}$=25, 50, and 100 MPa. Thus, the the shear strength mobilized quicker (at lower deformations) when for stiffer backfill. Hence, the deformations are lower (Figure 2) and most of the available resistance force are provide by the backfill material and less resistance will be activated in reinforcement which also corresponds to insufficient deformations for full mobilization of reinforcement strength. Comparison of the loads in reinforcements for backfill with different stiffnesses indicates that maximum loads are developed in the reinforcing layers in the backfill material with lower stiffness. The difference between the loads in reinforcement directly relates with the average mobilized friction angle in domain.
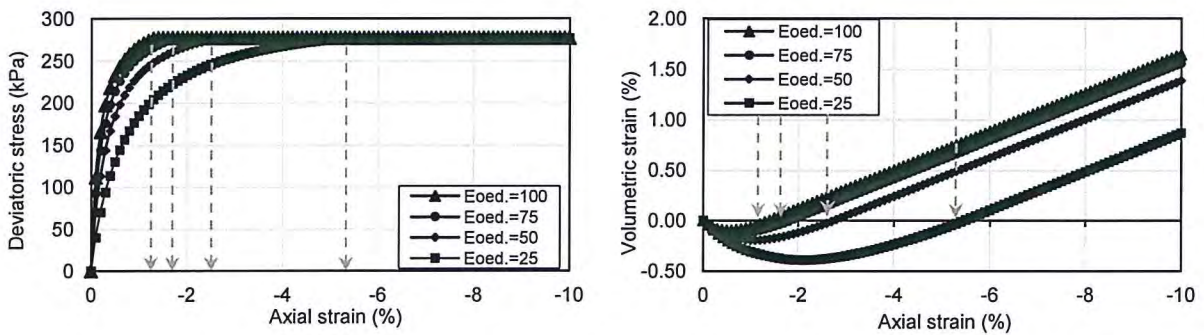

Figure 6. Strength and deformability characteristics of backfilling material through triaxial test

Loads developed in reinforcements

In this section, the influence of soil and reinforcement stiffness on the development of the force in the reinforcing layers at different height is studied. Figure 7 represents the variation of the maximum forces in reinforcement layers for different combinations of soil/reinforcement stiffnesses. Since the first 2 reinforcement layers are embedded in semi-rigid subsoil, no significant load has been developed in the lower 2 layers. Technically, these 2 layers act as a matters foundation which are subjected to lateral subsoil pressure. Accordingly, the results for the first two reinforcement layers are not shown in Figure 7. As seen, for backfill soil with lower stiffness ($E_{oed.}$=25 MPa), greater forces will be developed in the stiffer reinforcements. However, the forces in the reinforcement layers with low and high tensile stiffnesses tend to be identical when the back filling material is stiffer. This aspect can be particularly explained based on the mobilization of the shear strength in soil and its relation with mobilization of the tensile force in the geotextiles. As shown in Figure 7, the peak strain for stiffer soils are less than those correspond to soils with lower stiffness. Therefore, the total strength of the backfill is mobilized at larger deformations. However, the higher tensile forces are mobilized in accordance to lower strains for stiffer reinforcements. Therefore, higher resistance

forces will be available from reinforcing components at low strains when stiff geotextiles are utilized. Thus, higher loads will be developed in the reinforcement and less will be carried with the soil body. It is to be noted than even though the internal stability of the system has been satisfies, one should takes into account the higher loads developed in the grids which demands using reinforcements with higher tensile strength. On the other hand, the mobilization of the expected tensile strength at low strains due to using stiff reinforcements should be carefully taken into account in design process. This is of particular importance since the stability analysis just accounts for tensile strength which might lead to risky design due to letting higher loads to be developed in stiffer grids with identical tensile strengths particularly in backfill with lower stiffness. Regarding Figure 6, the maximum tensile force has been developed in 5th layer that is located at the height of 2m (i.e. $H/3$). To precisely determine the increase of working loads in reinforcing materials with different stiffness, the maximum difference ratio has been defined as the difference of the load developed in reinforcement with highest (EA=2000) and lowest (EA=500) stiffnesses which divided by the latter component as:

$$\text{Maximum difference (\%)} = \frac{F_{\max(EA=2000)} - F_{\max(EA=500)}}{F_{\max(EA=500)}} \times 100 \qquad [1]$$
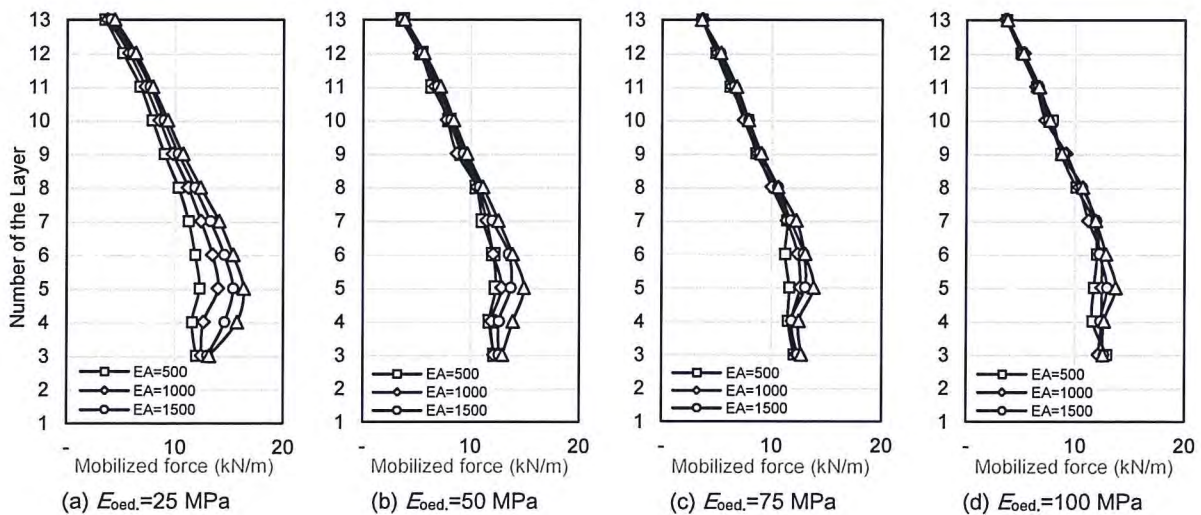

Figure 7. Variation of the maximum tensile force in different reinforcement layers
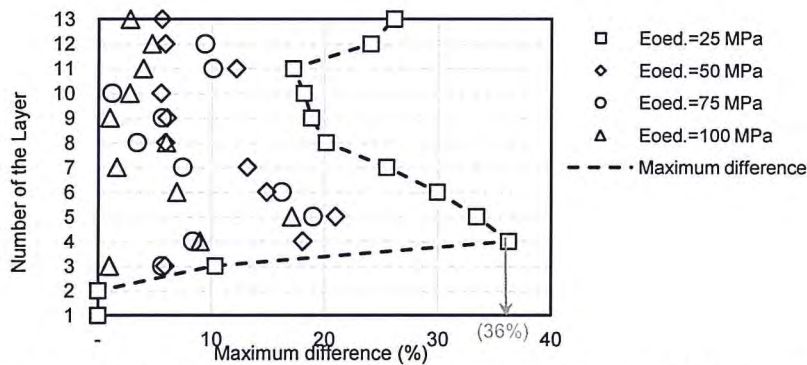
Figure 8. The difference between maximum loads in reinforcement with lower and high tensile stiffnesses

According to Figure 8, the development of the tensile forces in reinforcement is intensely sensitive to the stiffness of the reinforcement for backfills with lower stiffness ($E_{oed.}$=25 MPa). This sensitivity becomes less significant by increasing the stiffness of the backfill material. For extremely stiff soils, the average influence of the reinforcement stiffness on the developed forces is less than 10%, however, the maximum difference that occurs in 5th layer is still 17%. In addition, Figure 8 shows that using stiffer reinforcement can result in an increase in the developed tensile force in geogrid up to 36% which can jeopardize the stability of the wall system if this increase has not been considered in design process. As the main conclusion regarding the relation between forces and stiffness of reinforcement, it is to be emphasized that use of reinforcement with higher tensile stiffness cause a significant increase in the working loads in the geogrid layers. The designers should take this increase into account since the effect of the increase in load due to axial stiffness has not been reflected in the stability design concept. When the designer uses (or needs to use) reinforcements with higher tensile stiffness, he is also asked to reduce the peak friction angle for the design due to formerly shown effect. The common partial safety factors used in the design methods, do not account for this. To check the influence of the tensile stiffness on the conventional design procedure, the concept of geogrid tensile stiffness depending mobilization of the friction angle following the Jewell's approach (1985) was implemented in the stability analysis based on GGU-stability software. To make the stability analysis consistent with the FEM model, the short-term tensile design strength of the reinforcement has been considered by eliminating all reduction and partial safety factors. The concept of mobilized friction angle in the soil material has been considered by simulation of the domain where the average mobilized friction angle has been determined as a separate cluster (see zone of interest in Figure 1). The schematic shape of the model for stability analysis has been shown in Figure 1. The friction angle of the backfill material in this cluster has been assigned with respect to the average mobilized friction angles obtained from numerical analyses for flexible (EA=500 kN/m) and stiff (EA=2,000 kN/m) geogrids for backfill with $E_{oed.}$= 25 MPa (Figures 4a and 5a). The safety factor for the stability analysis following conventional design approach (full mobilization of friction angle) as well as partial mobilization of friction angle is shown in Table 2.

Table 2. Safety factor of the reinforced wall system against slope failure for short-term tensile strength

Description	Safety Factor for stability
Normal design approach ($\varphi_{mob.}$=35°)	1.81
EA=500 kN/m ($E_{oed.}$=25MPa, $\varphi_{mob.}$=29°)	1.51
EA=2000 kN/m ($E_{oed.}$=25MPa, $\varphi_{mob.}$=22°)	1.23

According to Table 2, the implementation on Jewell's concept of mobilized friction angle in the conventional design approaches can significantly affect the consequence of design. As seen, by the use of more stiff reinforcement, the less friction angle is mobilized and this results in lower safety factors. However, the conventional design approaches ignore the effect of soil/reinforcement stiffness as well as the mobilized friction angle concept.

Besides the aforementioned technical issues on using reinforcements with high tensile stiffness, there are several constructional concerns which can negatively affect the system behavior.

4. CONCLUSION

The influence of reinforcement stiffness (bending and tensile) on the system behavior, mobilization of strength and the forces in geogrid layers in a reinforced retaining wall has been numerically studied. With reference to the obtained results, the following remarks can be highlighted:

1. Using geotextiles with higher bending stiffness in soil can absorb the compaction energy and also eliminate the alignment component of interaction resistance between reinforcement and soil. Both of these aspects can weaken the shear strength of soil-geotextile contact.

2. There is a critical tensile stiffness of reinforcement that reinforcing the backfill with stiffer geotextile beyond that cannot decrease the horizontal deformations of the wall significantly.

3. Using reinforcements with higher axial stiffnesses significantly increases the tensile force in the geotextile due to imperfect mobilization of the stress in backfill material. This definitely can affect process of mobilization of strength in the reinforcement as well.

4. For backfills with low to normal stiffness, the conventional design approaches based on internal stability are not sufficient to be employed for the design of reinforcements with high tensile stiffnesses due to higher loads which are developed in the reinforcement by incomplete mobilization of soil strength.

5. If very stiff material is used in backfilling, the soil strength is fully mobilized at smaller deformations (strains) and therefore using stiffer geogrid does not develop higher loads in the reinforcement.

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