INFLUENCE OF GEOGRID PROPERTIES ON THE DEFORMATION OF REINFORCED STRUCTURES

Florian Bussert[1]

[1] *Tensar International Ltd. (e-mail: bussert@tensar.co.uk)*

Abstract: Properly constructed reinforced structures show extremely small deformations even when failure loads are exceeded. Numerous measurements in constructed structures and trial test walls indicate that only small geogrid strains need to be activated to establish the load carrying potential of the structures. When compared with design, strains in the field are even lower than the required strains to ensure equilibrium state.

To investigate the interaction between soil and geogrid a large scale biaxial apparatus 1.0m/1.0m/1.5m(length/ width/ height) was constructed in which soil and geogrid were tested without scaling effects. Analogous to the deformation behaviour of most reinforced structures plane strain conditions are simulated in the tests. A constant vertical load was applied on top of the composite material while a moveable side wall was shifted outwards horizontally. Stresses acting at the moveable side wall were measured continuously from at rest conditions until a residual stress was reached. Activated stresses within the composite material and the stress transfer inside the reinforced structure were calculated.

The load carrying capacity of the composite material is activated after small deformations and characterised by significantly smaller horizontal stresses than the non-reinforced soil. Stresses are controlled by geogrid and soil properties. The main effects contributing to the significant load carrying capacity are not taken into account in actual designs which leads to a significant underestimation of load carrying capacity and overestimation of deformation.

In the paper, details on the research results are given. Additional results of a field test constructed to prove laboratory findings are also presented.

Keywords: reinforced earth, deformation, aperture size, stiffness, stabilization, composite

INTRODUCTION

Over the last 20 – 30 years the design methods for geosynthetic reinforced soil walls that have been developed are generally accepted to be very conservative in determining the density of reinforcement required for a stable structure. This is a result from the monitoring of structures which has demonstrated a complete mismatch between the measured strains developed in the reinforcing layers and the loads that have been calculated in the design.

The inherent high factors of safety provided believe in geogrid reinforced structures in the past. However, recent developments have tried to identify and describe the mechanism that exists between geogrid and soil in order to achieve a better agreement between design and field behaviour of walls/ slopes. A better mechanical description of geogrid-soil interaction would enable a more economical design and would allow engineers to determine the expected deformation of structures during serviceability and under different loading conditions.

Therefore the identification of geogrid and soil properties influencing the stress transfer and deformation characteristics of the reinforced soil is the objective of this paper. Calculation of the external stability is not affected by the type of reinforcement chosen and therefore not dealt with in this paper.

Concept of calculating structural deformation and capacity

The basic assumption in the design of reinforced soil is that an active and a resisting zone exist and that the weight of the active zone has to be transferred by the reinforcement to the passive zone to maintain equilibrium and ensure a stable structure (figure 1). This requires the assumption of a sliding plane which is assumed to be present continuously, in Ultimate (ULS) as well as Serviceability limit state (SLS). The mechanical assumption in this approach is that the reinforcement develops adequate bond with the surrounding soil and has sufficient tensile strength and stiffness to withstand the required tensile forces to maintain equilibrium.

Tensile strains are developed in the soil and transferred to the reinforcement when sufficient bond can be established between the reinforcement and the soil. The soil-reinforcement bond raises a corresponding tensile force in the reinforcement (BS 8006). Stresses and therefore tensile forces are absorbed by the reinforcement in the active part and will shed these forces into the soil in the resistant zone. The available bond between geogrid and soil is investigated either by shear box for quality control purposes or pull-out test to assess load displacement characteristics with respect to serviceability.

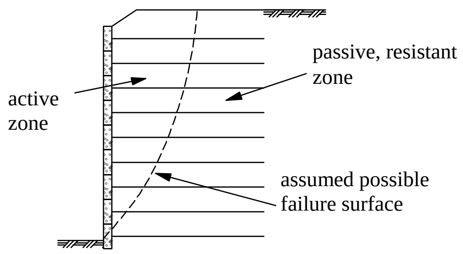

Figure 1. Determination of different areas according to BS 8006

Equilibrium between active and resistance zone is based on this principle and is calculated using a Limit State approach. Individual factors of safety are applied on each structural member in order to result in an efficient structure where the probability of failure of each member is harmonised with the others by changing the factors of safety. However, it is questionable whether the basic principle of this calculation method sufficiently represents the mechanical interaction of geogrid reinforcement and soil.

Limitations of actual approach

It has been shown numerous times in the past that the achieved geogrid strains in the field are much lower than the ones predicted by the calculations. Therefore it is expected, and has been shown that the failure loads are much larger than calculated. Measurements in the past did not show the assumed failure surface expected in design, indicating that the internal soil strains are smaller than the strain required activating residual values. As the surveys of structural facings have indicated virtually no deflection, it is obvious that the reinforced soil block behaves more rigidly than expected.

The stress-strain characteristic of unreinforced soil is a function of the confining stress σ_3. Assuming an idealised geogrid soil system as shown in figure 2, BS 8006 (1995) indicated that the magnitude of deformation of a reinforced system is a direct result of an additional confining stress $\Delta\sigma_3$, generated by and internal interaction between soil and the reinforcement.

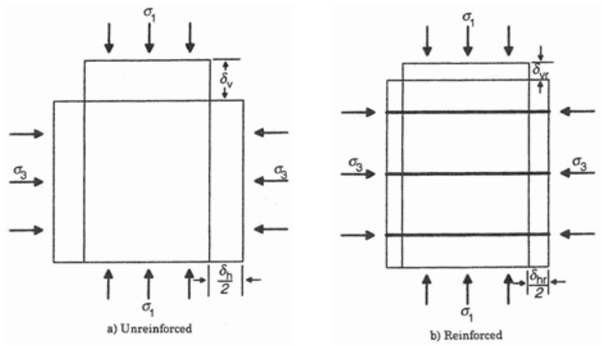

Figure 2. Schematic explanation of geogrid on reinforced material deformation behaviour

The factors in this interaction define the basic principles of reinforced earth. Provided the surface of the reinforcement is sufficiently rough, movement of the soil, relative to the reinforcement, will generate shear stresses at the soil reinforcement interface. These shear stresses induce tensile loads in the reinforcement which are redistributed back into the soil in the form of an additional internal confining stress $\Delta\sigma_3$. The magnitude of this confining stress on the soil has never been investigated and is neglected in reinforced soil design as from current used laboratory tests it is not possible to derive the increase in soil strength. When the soil is reinforced, a large value of σ_1 is needed to cause failure. This is because increments of σ_1 induce increments of $\Delta\sigma_3$ which lead to relative small increments in the applied shear stress $\frac{1}{2}(\sigma_1 - (\sigma_3 + \Delta\sigma_3))$. A practical limit is imposed on the strength of the reinforced soil either by tensile rupture of the reinforcement or a bond failure caused by slippage at the soil/ reinforcement interface.

To identify the increase in soil strength and to determine the main parameters influencing the geogrid soil interaction, it is necessary to construct a new test device that is capable of representing a multiple layered soil block. Additionally more realistic load transfer characteristics than used in current laboratory tests (e.g. pull-out, shear test) need to be incorporated as the load is transferred from the soil to the geogrid so that soil movement is restricted, while the fundamental assumption in pull-out tests is an exiting failure plane, causing geogrid elongation and the tension force has to be transferred back in the soil. It is essential that the test device does not introduce a specific failure plane to be able to investigate the material properties of reinforced soil in serviceability.

TEST DEVICE: BIAXIAL APPARATUS

To identify the boundary conditions of the test device an indefinite reinforced wall/ slope reinforced with several layers of geogrid is assumed. Only vertical deformation as a function of surcharge and horizontal displacement in direction of the facing, transverse to the wall/ slope axis is permitted.

To investigate the stress-deformation characteristics of a multilayered element out of the structure as shown in figure 3, plain strain conditions apply, while allowing a three-dimensional state of stress to develop. As the horizontal pressure in the reinforced soil is changing with increasing horizontal strain the load transfer in the reinforced structure can be investigated as a function of horizontal movement under constant vertical stress. Stress-strain properties are examined with different layer spacing, geosynthetic strength and material, geosynthetic aperture as well as grain size at different stress levels.

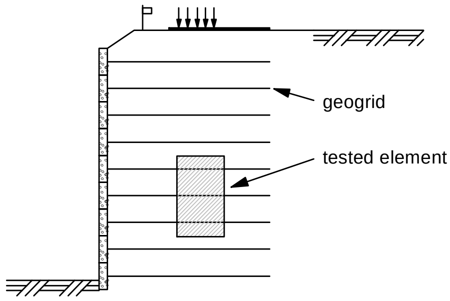

Figure 3. Investigated element out of a structure

The biaxial apparatus has dimensions of 1.0m/1.0m/1.5m (length/ width/ height) and consists of a base plate and four rigid side elements that are connected by rigid threaded rods as shown in figure 4. One side element (as shown on the right side in figure 4) is connected to a movable plate inside the massive frame (7) that can be shifted outwards with a accuracy of $^{1}/_{10}$ mm while the vertical pressure is kept constant (Bussert, 2006). The stress controlled vertical load is applied via a hydraulic cylinder connected to a loading frame. The applied vertical stress, horizontal stresses on the movable plate, stress acting perpendicular to the movement as well as settlement of the loading plate and movement of the plate are measured throughout the test by strain gauges, load cells and displacement transducers.

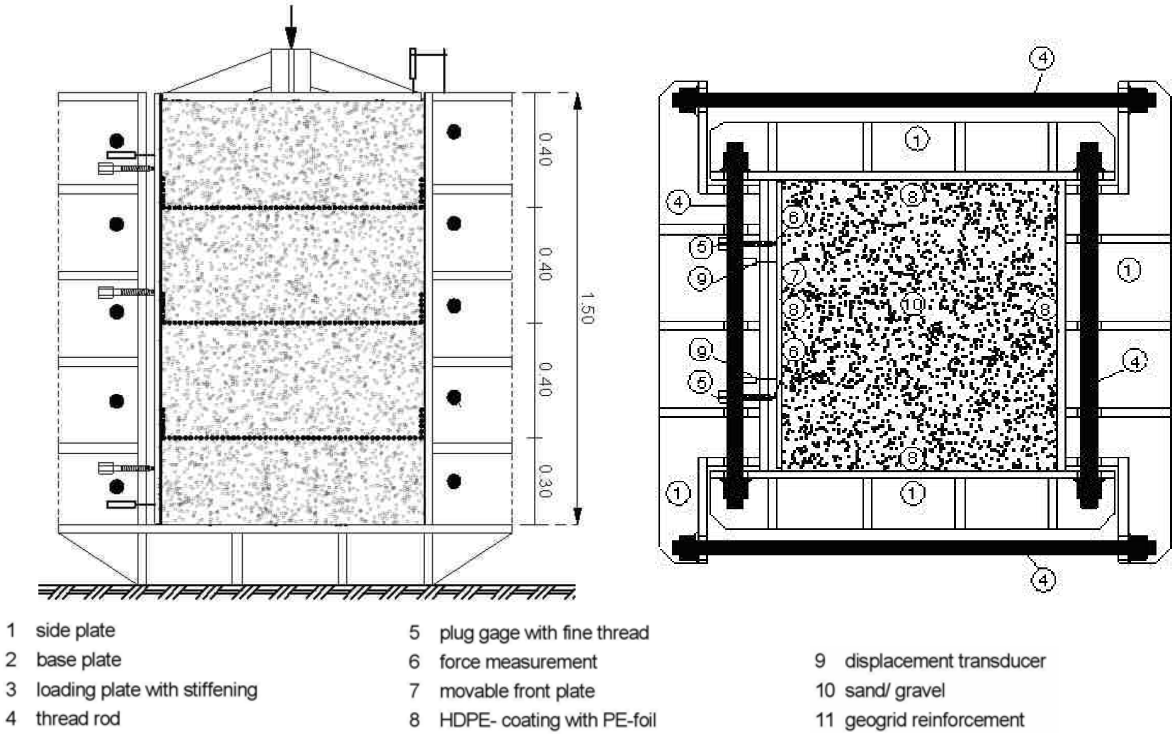

Figure 4. Cross-section and top view on biaxial apparatus

Installation and test procedure

Sand (0-2 mm) and gravel (2-12 mm) were used in a dense/ medium dense state. To ensure representative and uniform soil conditions throughout the whole test series, and to prevent apparent cohesion, dry soil was used. Different commercially available geosynthetics with varying properties were tested. They were placed in the apparatus at layer spacing varying from 0.2m up to 1.0m. A controlled installation procedure ensures uniform granular density throughout the filling process. Before installing the geogrids the soil surface was levelled and made smooth. The geogrids were slightly bent at the side to ensure continuous straining during the test procedure. Afterwards the next soil layer placed in the apparatus by a hopper. When installation of geogrid and soil was completed, the loading plate was placed and the vertical pressure applied.

After the target pressure was reached, the movable plate was shifted outwards in increments of 0.1mm while the vertical stress was kept constant. While the horizontal plate is moved outwards, the pressure on the side wall decreases as a function of the activated shear stresses in the soil, tensile forces activated in the geogrids and the geogrid-soil interaction. The definitions used are indicated in figure 5. An unreinforced soil leads to a remaining pressure on the side wall σ_{Ph} equal to $1\text{-}k_a/k_0$, while a reinforced material with perfect geogrid-soil interaction would absorb all initial horizontal stresses resulting in $\sigma_{Ph}=0$.

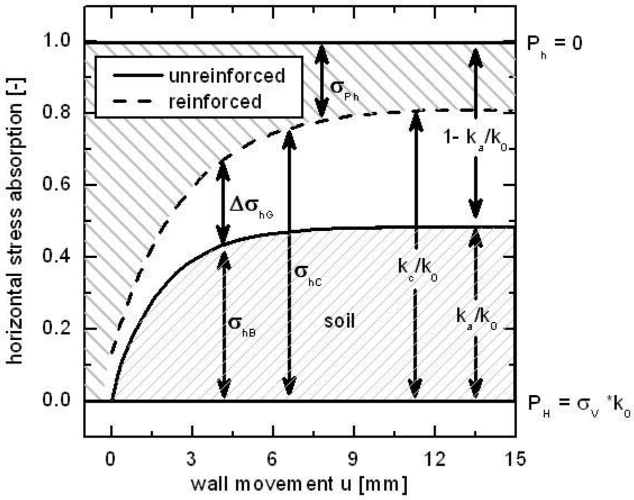

Figure 5. Definitions of stress absorption in the reinforced system

After a residual horizontal stress was observed, higher vertical stresses were applied and the moveable plate shifted outwards further to reach the residual horizontal stresses under higher surcharge. Additional tests proved that the initial activation of shear stresses in the first loading step does not influence the residual value and that the results can therefore be normalised with respect to the vertical load. Extensive data was obtained in this way to investigate the stress-strain behaviour load transfer characteristics within the reinforced soil.

TEST RESULTS AND INFLUENCING PROPERTIES INVESTIGATED

Layer spacing

First the influence of the layer spacing was investigated for different geogrids. Figure 6 (left) shows the effect of uniaxial geogrids placed in sand at different spacing. The continuous black line indicates the activation of shear stresses in unreinforced sand. With increasing wall movement the horizontal stress decreases from the earth pressure at rest (k_0) to the active earth pressure (k_a) as the shear resistance is activated in the soil. As expected, higher stress can be activated in the reinforced soil, resulting in reduced horizontal pressure σ_{Ph}. The increase in activated stress in the reinforced system increases with decreasing layer spacing. When the horizontal stress reduction reaches 45kPa, no support is necessary from the horizontal wall, as a self supporting system will have been activated. When a maximum stress for a specific system is activated (horizontal line, constant σ_{Ph}) no further shear stresses can be activated in the reinforced soil, even though the wall movement continues which results in higher geogrid tension forces. With decreasing layer spacing, the wall movement to activate the residual horizontal stress decreases. This indicates a stiffer material behaviour of the reinforced soil compared to the unreinforced. As the geogrid-soil material is not compacted, small initial movement is necessary to activate the geogrid-soil interaction.

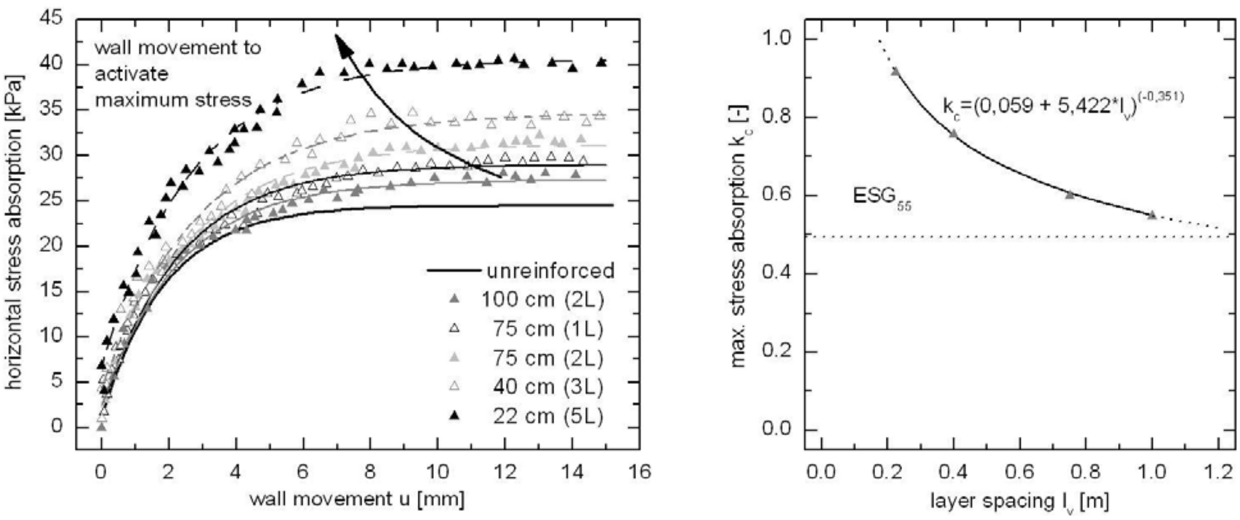

Figure 6. Influence of layer spacing on horizontal stress absorption, σ_v=120kPa, sand

Comparing the activated stress within the reinforced soil with the initial earth pressure at rest (k_0) shows the geogrid-soil interaction efficiency (figure 6, right). A value of 1.0 indicates that all initially present stresses (k_0) are activated within the reinforced soil and no support is required. The dashed line shows the stress reduction achieved by the unreinforced sample. The reinforced sample activates additional stresses resulting in increased stress absorption within the reinforced system. As the activated stress is plotted versus layer spacing, a tendency towards a linear horizontal pressure reduction can be estimated up to a critical value. When the layer spacing is reduced further an exponential increase in activated stresses is observed. This indicates a stiffer material behaviour of the reinforced soil. The stiffer material behaviour is also indicated by reduced vertical displacement required to achieve the residual pressure and a reduced horizontal movement required to fully activate the load carrying capacity of the reinforced soil.

A similar relationship was found for every geogrid investigated; however, large variations exists in the efficiency of each geogrid as well as the required layer spacing from which on an exponential increase in the stress absorption can be measured. The efficiency of the geogrids used changes the acting horizontal stresses, showing the importance of the geogrid properties and the manufacturing process on the behaviour of the reinforced soil.

Soil grain size

Figure 7 (left) shows the stress absorption of the geogrid-soil material when a different grain size distribution with equal shear properties is used at similar layer spacing. The line of maximum activated stress within the reinforced material is shifted to the right. This indicates that a geogrid-soil material with increased or reduced shear properties can be developed with the change of the grain size. Different layer spacing can be used to obtain a comparable stress field in the reinforced soil. With equal spacing for different soils different stresses can be absorbed by the material. This results in higher or lower stresses that can be carried by the reinforced structure before reaching failure loads.

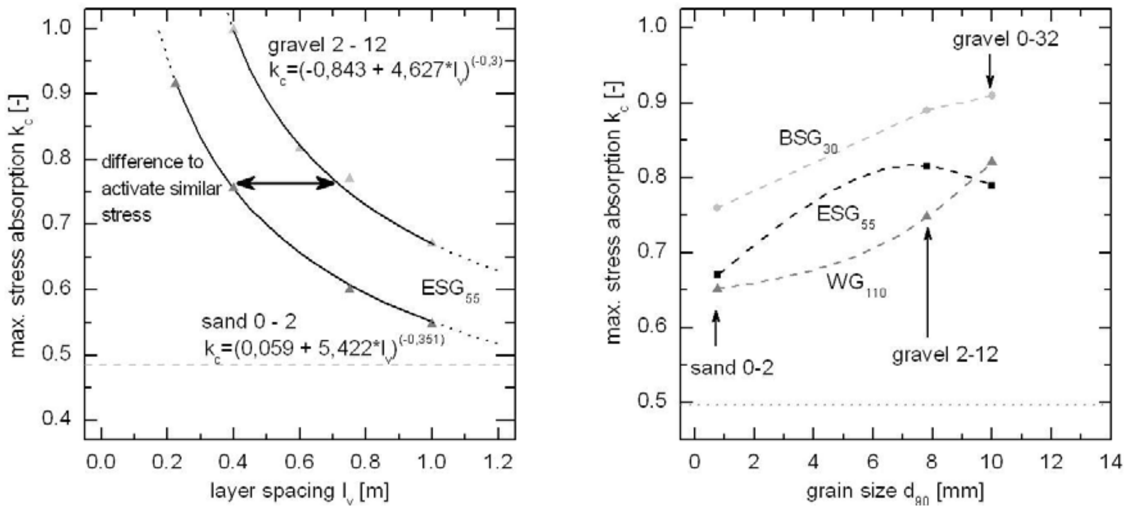

Figure 7. Influence of grain size on horizontal stress absorption

Figure 7 (right) shows the stress absorption measured at a layer spacing of 0.6m for different geogrids and grain size diameters d_{90}. It is obvious that all geogrid-soil materials exhibit a different material behaviour with varying grain size. While some geogrids may show reduced soil stress absorption once the ideal grain size is exceeded other geogrids can still show an increased performance. This shows the importance of clearly identified material properties for geogrid and soil in the reinforced structure to develop individual failure loads for reinforced structures or to estimate the deformation behaviour under various loading conditions.

Aperture size and shape

In a similar way to grain size the reinforced soil material properties change when the aperture size varies. When the ratio of aperture size to grain size is changed by the aperture, different stresses are activated in the reinforced soil.

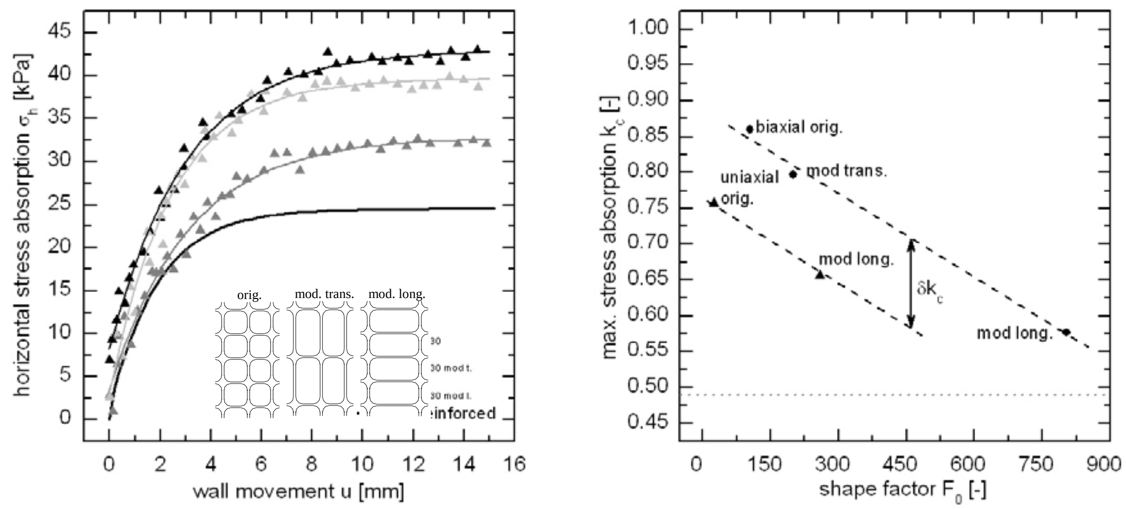

Figure 8. Horizontal stress absorption σ_h, modified apertures; l_v: 0.4 m, σ_v = 120 kPa, sand

The results of different aperture size on the stresses that can be absorbed are shown in figure 8 (left). A biaxial stretched geogrid was manually modified to achieve different aperture shapes. As shown, in the first test every second transverse bar was removed while for a second test every second longitudinal bar was removed.

The change in stress that can be absorbed by the reinforced material is a function of aperture size and shape. When the aperture increases, more soil movement can take place leading to reduced geogrid efficiency. When the stress absorption is plotted versus a shape factor that was derived from the aperture form, shape and rib thickness, it can be seen that a linear relationship of stress absorption and shape factor can be established (figure 8, right). With increasing shape factor, the efficiency to prevent movement in the aperture reduces, resulting in a lower capability of the reinforced soil to develop increased shear stresses within the system.

By producing additional geogrids with specific shape factors, the relationship was proven for predicted values. These grids were additionally manufactured with different tensile strength. Therefore it could be shown that the geogrid strength does not influence the material properties of the reinforced soil. Additionally it can be seen from figure 8 (right), that the manufacturing process has an influence on the stress reduction that can be achieved by the geogrid-soil. The different δk_c denotes the difference for punched geogrids that are stretched uniaxially and biaxially. Different manufacturing processes in the meanwhile result in a different slope of the vertical line and different starting points.

Aperture stability

Changing the aperture size by cutting single elements out of the structure, results in a change in the aperture stability. As the rib lengths between two bars increases the geogrid structure becomes more flexible, so that the apertures have a reduced stability and stiffness against torsion and bending of the elements that otherwise stabilize the soil. To investigate the importance and the effect of changing aperture stability, different geogrids with nearly similar aperture size and comparable tensile strength were investigated. As the aperture stability decreases a significant reduction in the achieved stress that can be activated in the system is noted. As before this means that different failure loads exist for all reinforced structures. Additionally different material behavior and therefore deformation of the different reinforced systems are observed during serviceability, showing the importance of the mentioned geogrid properties. As shown in figure 9 (left), the change in aperture stability changes the shape of the curve representing the stress activation as well as the maximum stress absorption that can be achieved. Especially the initial part of the stress activation curve is highly influenced by the aperture stability. While some geogrids show a behavior nearly like an unreinforced soil, others exhibit substantial better stress absorption even at very low strains. When comparing the geogrid secant modulus at the strain required achieving the residual value σ_{Ph} it can be seen that a strong influence is reached once a specific modulus representing aperture stiffness can be activated by the geogrid. Variations of the aperture stiffness above and below the specific stiffness value do not have a major influence on the material properties of the reinforced soil.

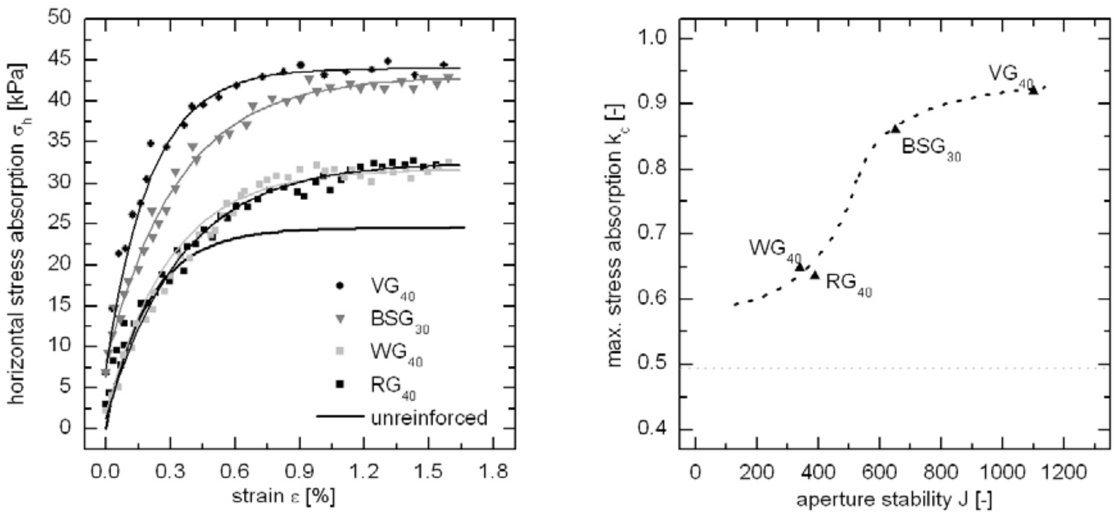

Figure 9. Horizontal stress absorption σ_h, versus aperture stability, l_v: 0.4 m, sand, σ_v = 120 kPa

Soil movement around the geogrid

It has been shown that numerous geogrid material properties that are not taken into account in day to day design of reinforced structures can have a significant influence on the deformation and load carrying behavior. It was shown from the material properties of the reinforced soil that the capability of the geogrid to restrict movement of soil particles in the apertures influences the properties of the material behavior. To further investigate the effect of the geogrid on the soil and to prove the importance of particle movement restriction, soil movement around the geogrid was measured at different vertical distances to the geogrid while the moveable plate was moved outwards.

Figure 10 shows soil movement at different distances from the grid as a function of wall movement. For a better illustration the values are mirrored at the centerline between two geogrids placed at a spacing of 0.4m. After a wall movement of 3mm soil movement around the geogrid is nearly constant throughout the reinforced soil, indicating constant shear stress activation. As the wall movement increases to 7mm it becomes obvious that soil movement in the vicinity of the geogrid is restricted by the geogrid. When the distance to the geogrid increases, soil particles are not confined and exhibit stress-strain characteristics as unreinforced soil. The more efficient the soil confinement by the geogrid is, the larger the influenced area around the geogrid becomes. Additionally the influenced area is controlled by the soil properties.

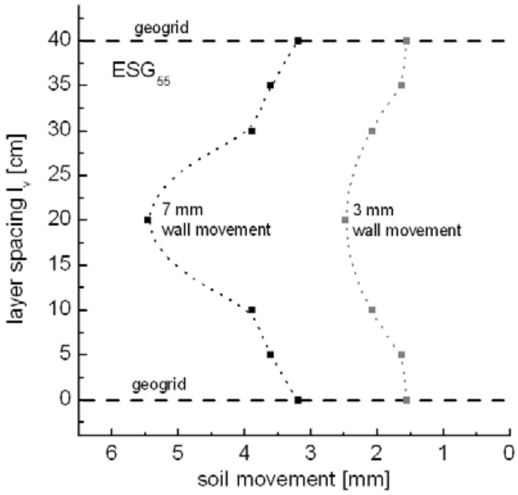

Figure 10. Soil movement in the geogrid-soil material, uniaxial geogrid, sand, σ_v = 120 kPa

When the influenced areas around the geogrid are intersecting each other, the developed composite material shows different material characteristics from the unreinforced soil. The composite material properties cannot be derived from the soil parameters. Due to the confinement the shearing resistance and young's modulus increase resulting in a stiffer material behavior and therefore reduced deformation of the material. This clearly indicates that an identification of soil parameters based on index tests underestimates the frictional properties in the reinforced material in serviceability limit state. The geogrid soil interaction enhances the soil parameters and therefore the properties of the reinforced material. As the material properties further depend on the geogrid strain activated, the material properties cannot be described by separate description of soil and geogrid properties.

Composite material properties

As shown, the interaction between geogrid and soil improves the material properties of the composite material. As the horizontal pressure decreases as a function of soil confinement, smaller horizontal shear stresses develop in the material. The tensile loads induced by these shear stresses have to be carried by the geogrids. As smaller tensile loads are required to achieve equilibrium of soil and geogrid, smaller geogrid strains need to be activated. This is similar to the small strains values measured in the field. At lower strain levels geosynthetic materials develop smaller creep strain so that the service life is exceeded significantly.

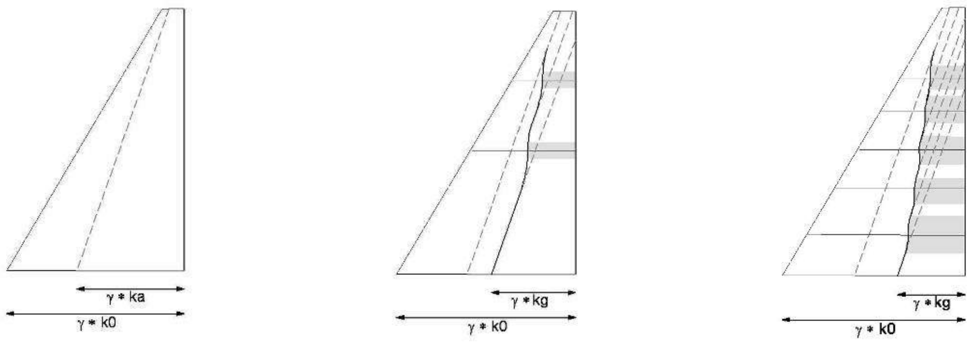

Figure 11. Influence of multiple geogrid layers on the horizontal pressure in the composite

The residual stress distribution in the reinforced structure can be calculated depending on the layer spacing and the influenced area around the geogrid. As shown in figure 11, the unreinforced soil initially develops a horizontal stress $\gamma * k_0$. Once sufficient movement was activated, the acting horizontal stress reduces to $\gamma * k_a$. Assuming a specific influenced area around a geogrid placed at large spacing the horizontal stress that has to be restricted by the geogrid decreases based on the material properties of the composite material. When the vertical spacing of the geogrid is reduced, a linear reduction of horizontal pressure present can be derived assuming a constant influenced area around each geogrid. Design according to the reduced horizontal pressure in the composite material significantly reduces the required geogrid strain and represents the material behaviour in a more economic way. If the influenced areas of each geogrid overlap each other, the stress transfer in the material and the failure loads of the composite material have to be calculated based on the material properties of the composite.

Figure 12 shows the comparison of horizontal and vertical as well as measured stress for a composite reinforced with a uniaxial geogrid. The continuous lines represent the theoretical values of earth pressure at rest and the active condition. Additionally the result of a uniaxial reinforced composite is shown. Due to the confinement of soil particles during construction in the composite material a lower "at rest" condition is achieved during initial loading (initial stress absorption). As horizontal movement under a constant vertical pressure takes place the horizontal pressure acting on the side wall decreases. As shown, the residual value is substantially smaller than the active earth pressure. As the composite material is further loaded with a higher vertical surcharge, only small increase in horizontal loads can be measured. In the subsequent wall movement, the horizontal pressure reduces again.

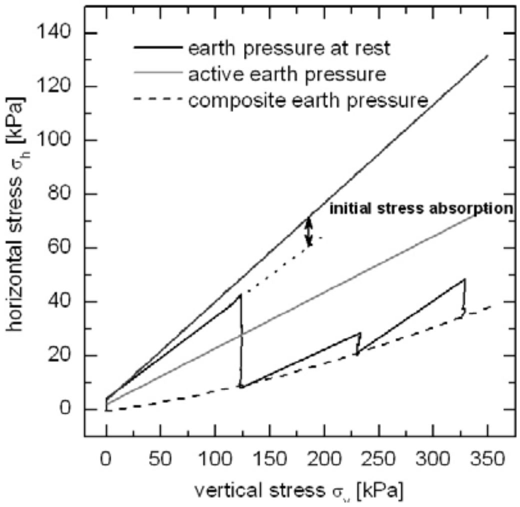

Figure 12. Comparison of earth pressure at rest, in active condition and representative for composite material

By initially loading directly to the second surcharge it was proven that the residual value achieved is independent of the initial loading. From these loading and movement sequences a relationship for individual earth pressures that have to be taken into account for different composite material were established. They show that the residual horizontal pressure k_c varies for every composite material based on the material properties of the geogrid. Based on these values and the stress-strain properties developed deformation characteristics and required tensile strength of the geogrids to ensure force equilibrium throughout the design life can be established.

TRIAL TEST WALL

The investigated material properties of the composite material that can be achieved by the combination of geogrid and soil have been further investigated in a trial test wall with a height of 9.6m. All mentioned dependencies were proven in this structure. The structure was constructed in several sections with varying soil and geogrid parameters. Except in one section of the structure, the geogrids used were chosen to be below the minimum strength required according to actual design procedures. However, the measured geogrid strains are in the same range as the values measured in all structures that are designed according to the design methods.

This indicates that the benefits of all factors described here should be considered in design. Therefore the theoretically calculated load capacity as well as related deformations would be comparable to the values measured in the field.

The results of the trial test wall will be presented in appropriate publications in the future.

Corresponding author: Dr Florian Bussert, Tensar International, Cunningham Court, Shadsworth Business Park, Blackburn, BB1 2QX, United Kingdom. Tel: +44(0)1254 262431. Email: bussert@tensar.co.uk.

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