ram reports in applied measurement

Measuring the stress and deformation behavior of soil retaining structures reinforced with synthetics

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Fig. 1: The green "outer skin" of a synthetics-reinforced support structure on a motorway in England

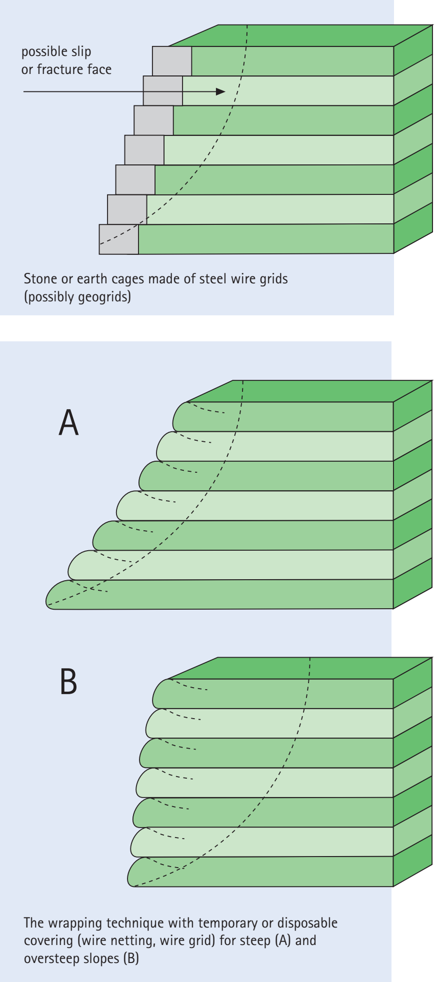
To determine the stress and deformation behavior of soil reinforced with synthetics, large-scale testing was carried out in a specially developed biaxial device ($V = 1.5\ m^3$). Because a special structure had to be designed for this topic, the measurement technique also had to be specifically developed for the device and the particular assignment. With the chosen solution, there was extremely good concordance of measured values and calibration values. The measurement technique allows the horizontal stresses of the biaxial device to be measured with increasing wall deformation and strain of the synthetics inserted in the soil. The results extend our knowledge of the bearing action of synthetics and soil in the working load range.

Introduction

The planning and implementation of earthworks and foundation structures is marked by extremely complex load bearing performance between the soil and the structural element. While the stress/strain behavior of "artificial" building materials such as steel, concrete or plastics can be determined within sufficiently narrow limits, there are many factors that can cause the behavior of the soil to vary, for example the geological history, the state of stress, the particle size or the water content. So a description of the mechanical properties is only possible within wide boundaries or for individual cases.

In recent years, soil retaining structures with synthetic reinforcement (SRS) have become established in civil engineering as the high-quality, economical and ecological alternatives to massive supporting structures made of concrete, stone blocks, etc. An SRS has a layered structure, made up of soil to a depth of 0.30 – 0.60 m, with intermediate layering of synthetics with isotropic or anisotropic resistance to expansion and a further layer of soil up to the planned slope height.

By using geosynthetics of different tensile strengths, it is possible to make stable structures of the requisite height, as the synthetics add an artificial tensile strength to the purely pressure-proof soil and produce a new composite material that can discharge both the compressive and the tensile forces. The front of a slope, a typical example of which is shown in **Figure 1**, is braced by a covering of geosynthetics or by a facing **(Figure 2)**.



Stone or earth cages made of steel wire grids (possibly geogrids)

The wrapping technique with temporary or disposable covering (wire netting, wire grid) for steep (A) and oversteep slopes (B)

Fig. 2: Structural shapes and slope inclines for the construction of synthetics-reinforced earth structures

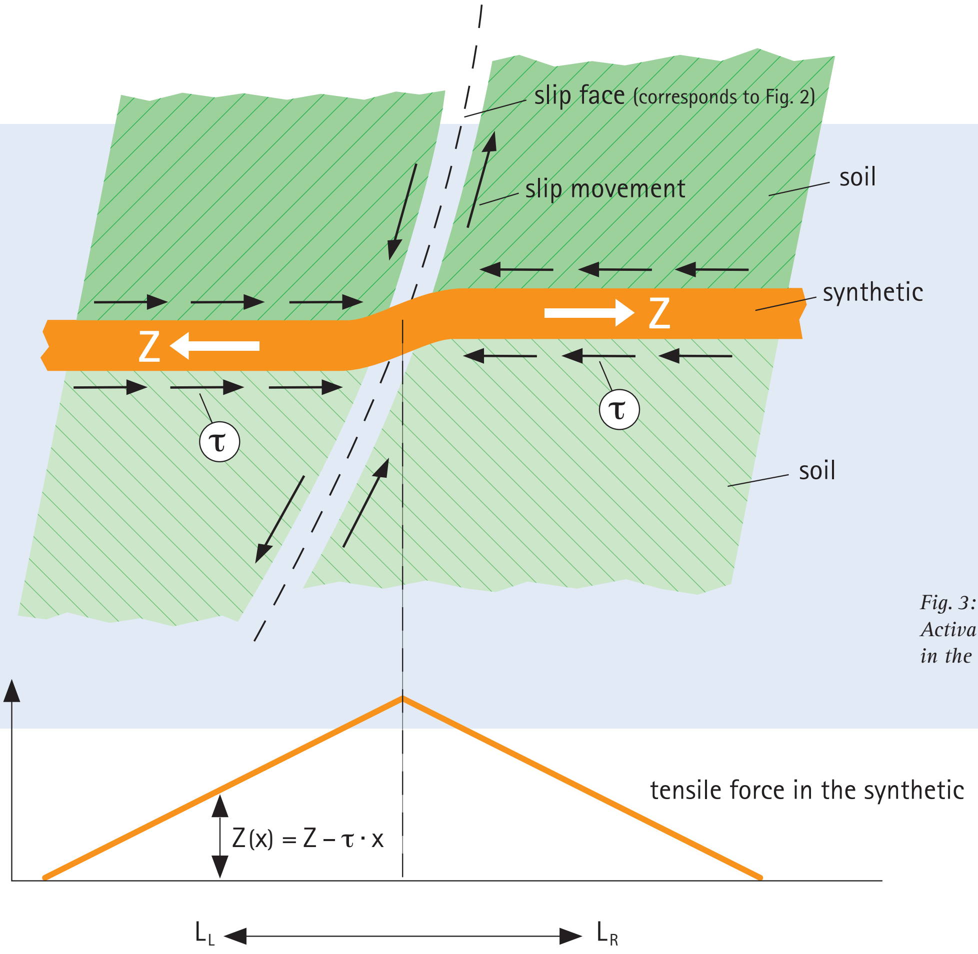


Fig. 3:
Activation of tensile force
in the geosynthetic

So depending on the aesthetic requirements, slopes can be created that blend perfectly into the scenery **(Figure 1, page 11)**.

The synthetics used either cover a large area (woven fabric) or have a grid-like construction. Grids are normally used to reinforce SRS, because the fill material and the soil can engage better.

The synthetics used are HDPE, PES/PET, PA, AR or PE, with, depending on the basic material individual struts and beams (longitudinal and transverse bearers) being welded, woven or extended. As the behavior of the synthetics is dependent on time, load and temperature, various safety factors are applied during SRS assessment, that take into account deterioration of the installation, behavior under long-term stressing and chemical and biological attack. There are various assessment approaches and detection methods for determining the bearing strength and permissible loading for SRS structures, such as [1] and [4], which have largely been taken over from the "reinforced earth" (steel reinforcement) rules of calculation. As with steel reinforcement the beams are only one-dimensional, the SRS calculation is only made on the basis of the stress/strain behavior in the synthetic struts. This means that the improved bearing strength brought about by this two-dimensional synthetics structure is not taken into account in this type of assessment. It is the transverse struts in particular that cause a totally different load bearing performance, that cannot be adequately recorded using this assessment method.

Also, because of their very much greater rigidity, the steel bearing elements are under strain over virtually the full length of the steel, whereas because of their much better flexibility, synthetics are mainly only under strain locally at the slip face **(Figure 3)**.

Because of the creep characteristic of the synthetics, reduced, short-term strengths are used in the assessment in order to ensure bearing strength at the end of the assessment period as well. This implies that because of the strain, ever greater deformation of the surface of the SRS on view would have to occur in time. But in the diverse projects that have been executed, only very little structural deformation has been determined during use (vertical and horizontal), which moreover, was within the bounds of measurement accuracy.

Fig. 4: *Slope section for determining the stress/strain behavior of the composite structure*

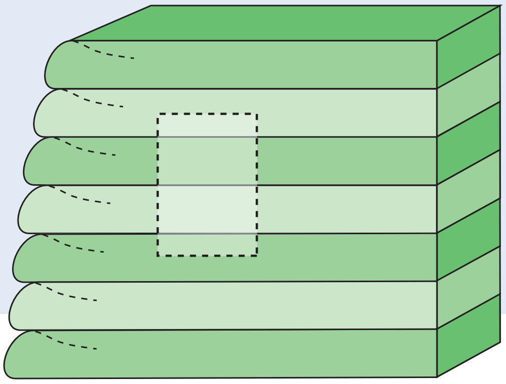


Fig. 5: *Large-scale axial device incl. loading structure at the Institut für Geotechnik und Markscheidewesen*

So it may be supposed that if the assessment of the SRS structures were to be optimized, more economic advantages could be expected. It is necessary to know how the soil and the synthetic interact, in order to describe the material behavior of the composite structure more precisely. Once this interaction is known, the deformation of the SRS in the working state can be judged, which, for example, would put local authorities in the position of being able to estimate the maintenance costs.

Test equipment for determining the stress/deformation behavior

In order to determine the stress/deformation behavior of SRS, it is absolutely essential to know the deformation within the structure and the interaction of the synthetic and the soil. Field trials [2] are useful to validate the assumptions made. But these are not usually enough on their own to explain the phenomena, as providing complete instrumentation is a very costly business. Also, numerous outside influences interfere with the measurement results from field trials and this makes it difficult to get at the precise meaning of the results.

For this reason, the Institut für Geotechnik und Markscheidewesen at the Technische Universität Clausthal, Germany, designed a large-scale test device, in order to provide greater understanding of the stress/deformation processes occurring in an SRS. The aim was to determine realistic assessment principles, according to which it would be possible to demonstrate the bearing strength and the performance capability of geosynthetically reinforced support structures.

Large-scale biaxial device

The basic idea behind the exploratory focus is the investigation of a section from a slope **(Figure 4)**.

The large-scale biaxial device (w x l x h = 1.0 x 1.0 x 1.5 m) that can be subjected to pressure controlled and displacement controlled forces of up to 1000 kN at a frequency of 4 Hz via a framework construction, is shown in **Figure 5**.

It comprises a base plate and four rigid side elements, of which each of the two opposite pairs are connected with five massive threaded rods on each side. In addition, the diagonal sides are each fastened to the base plate by five M36 screws. To measure the pressures acting on the side pieces three HBM T rosettes (XG11-6 /120) are installed on each of the threaded rods at a cross-section with 120° spacing, to exclude torque and radial stress. The strain gages are connected as a half bridge with temperature compensation to compensate for the effects of the increase in lab temperature because of the loading unit.

In order to be able to specify controlled deformation starting from one side of the biaxial device, a steel plate that can be moved with 1/10 mm accuracy on six support points developed as bolts, was suspended in front of one of the side pieces. The bolts are connected to the side piece by a fine thread and relay the horizontal forces acting on the plate to the side piece. Overall, it is possible to achieve a horizontal shift of 4 cm **(Figure 6)**.

As preliminary tests had shown that it was not possible to measure the forces acting on the suspended plate via the threaded rods arranged at the sides accurately enough because of the high frictional forces of the side pieces on the base plate, the bolts were converted into measuring bolts. In the front section, three T-rosettes were likewise installed at an angle of 120° (once again as a half bridge with temperature compensation) **(Figure 7)**.

The measuring bolts were calibrated under a ram at different temperatures. **Figure 8** shows the correlation between the applied load and the measured load at the various temperatures for two of the six measuring bolts.

To test the operational capability of the measuring bolts in the biaxial device, different compressive forces were applied to the suspended plate by a ram installed in the biaxial device. These compressive forces were measured by an HBM C4–50 kN force transducer and compared with the total measuring bolt forces. Once again, the accuracy of the measuring equipment was found to be excellent.

Test installation and test implementation

Sand and the geosynthetic were inserted into the biaxial device in layers. The spacing between the geosynthetics was 0.40 m. The first layer of sand was 0.30 m deep. To ensure that the chosen soil compaction remained of an even quality, the sand was trickled in from a constant height.

A special trickling device was designed for this, with both the trickling height and the hole diameter in the perforated plate located on the underside of the trickle box being adjustable. This made it possible to create different compactions for the incorporated soil. The volume of the trickle box was 0.15 m^3, the material it was filled with was measured by a U2B-20 kN force transducer from HBM, so

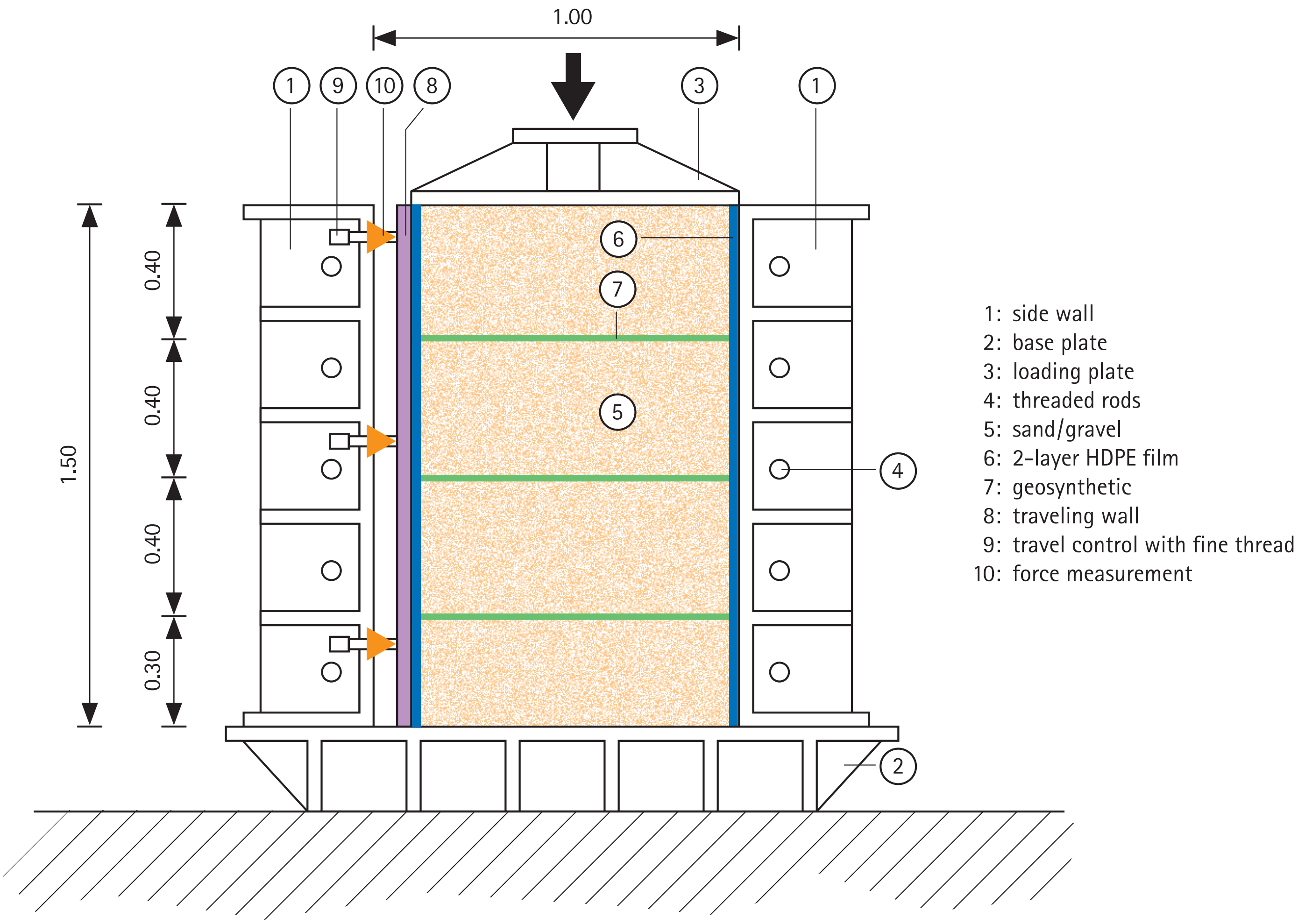


Fig. 6: Section through the biaxial device, structure of the test piece

that the created density in the biaxial device could be continuously determined. The surface of the sand layer was smoothed off and the synthetic, which was cut to be an exact fit, was placed on top. Then the new trickle height was determined and the next layer of soil incorporated.

Using this application technique, it was possible to obtain compactions from loose to average density. To obtain greater compactions, which would allow the synthetic and the soil to engage better, the soil is trickled in as described above, in layers, but then also put under pressure with a vibratory plate with a given oscillating frequency and time unit.

During the buildup, the bolt forces are measured continuously, in order to detect any differences in comparison with the theoretically determined earth pressure that would result in inexplicable test results.

The pressure acting on part of the soil in the subsoil increases linearly with the depth (σ_V). This so-called earth pressure at rest is defined by the weight of the soil γ and the height of the overlay h. The horizontal stress (σ_H) also increases linearly with the depth, but this is dependent on the friction angle ϕ (angle of slope) of the soil. The associated horizontal stress is defined by:

$$\sigma_H = k_0 \cdot \sigma_V \qquad (1)$$

$$\sigma_V = \gamma \cdot h \qquad (2)$$

$$k_0 = 1 - \sin\phi \qquad (3)$$

If soil movements are admitted, this reduces the earth pressure to be supported. The minimum possible pressure (minimum horizontal support required) is the active earth pressure, at which all the transverse forces acting along a slip face were activated. A further reduction from the soil mechanics point of view is only possible if stabilizing forces are also available within the earth structure to absorb the (tensile) forces necessary for further reduction. In the case of an SRS, this is done by the synthetics.

The tensile forces of the synthetics are activated with increasing strain. To determine interaction of the soil and the synthetic, the geosynthetic strains have to be measured. To do this, a 0.25 mm thick spring steel was equipped with strain gages. As the low section modulus of the spring steel can cause bending effects, strain gages were installed on each side (half bridge with temperature compensation), in order to be able to calculate and eliminate the changes in length as well as the bending effects. The synthetic and the spring steel were solidly connected with clamps designed specifically for this purpose **(Figure 9)**. The variable clamps allowed the strain between the two struts or beyond the struts to be measured.

Fig. 7: Front part of the measuring bolt with the T rosette XG11-6/120 SG from HBM, with the pin to which the plate is attached in front

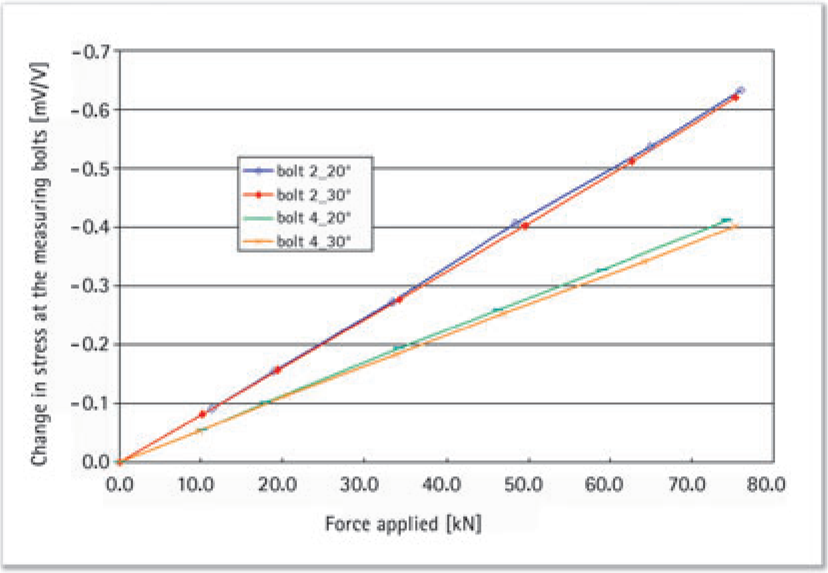


Fig. 8: Measuring bolt calibration data, shown for bolts 2 and 4

Fig. 9: Exposed spring steel for strain measurement of synthetics, LY11-6/120 SG from HBM

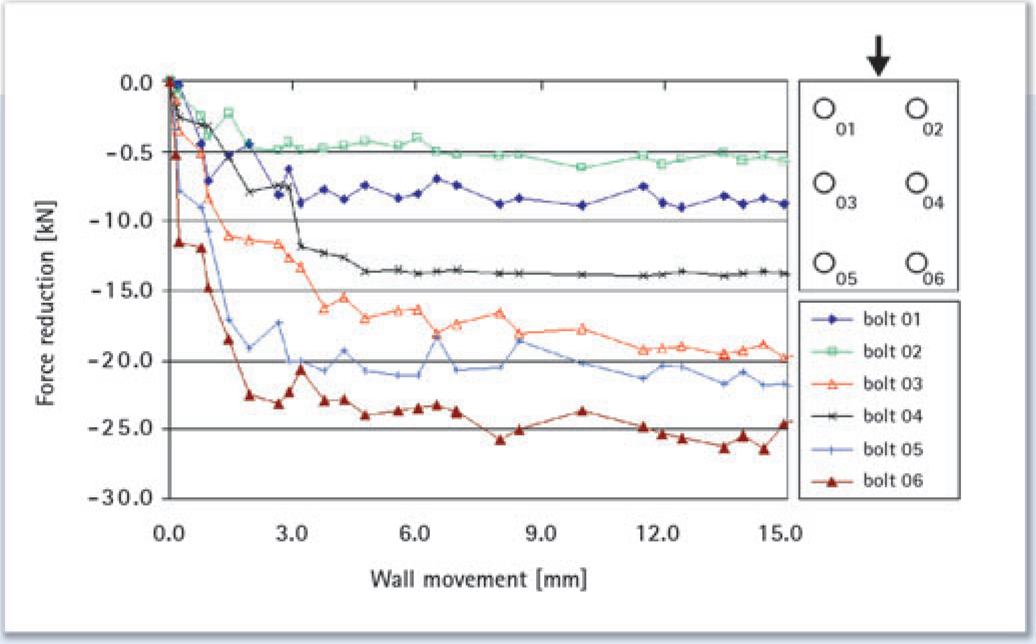


Fig. 10:
Reduction of the forces acting on the individual bolts as the wall movement increases

Tensile testing carried out beforehand showed that the influence of the more rigid measuring steel on the stress/strain behavior of the synthetic is only very slight and is within a range that is not relevant to construction practice. The measured stress/strain behavior of the synthetics with the installed strain gages is within the manufacturing accuracy range of the stress/strain behavior of the synthetics themselves. To stop the strain gages being damaged, they were coated with silicone rubber and in addition, protected by shrinkdown plastic tubing that was replaced before each test.

Control and measuring equipment

Once installation is complete, the loading plate is attached and the inductive HBM displacement transducers with plungers for measuring the cylinder travel (WA 300) and the settlement of the loading plate (WA 200) are fitted. Four inductive displacement transducers are installed on the corners to record the inclinations of the loading plate. To simulate the section from a slope at a depth of approx. 7.0 m, a constant load of 135.0 kN/m^2 (kPa) is applied and the sideways acting compressive force is measured. As the wall deformation increases, this gets less, as the transverse forces of the soil and the stabilizing forces of the synthetics are activated.

For the static tests, all the measured values from the strain gages and the force and displacement transducers are measured automatically at a frequency of 0.2 Hz by the HBM measuring amplifier MGCplus. When there is additional dynamic loading, the test frequency is increased, in order to accurately record loading and relieving. The wall is moved in 0.25 mm increments. After each wall movement, a quiescent condition is awaited, as the wall movement produces an increase in the surface area of the earth while the volume remains the same. After these movements, the cylinder must first adjust the vertical force back to a constant level. The wall shift data monitored constantly by three inductive displacement transducers (WA 200) for optimum test implementation, the vertical compressive force and the bolt forces are traced on the monitor and once the quiescent condition is observed, further wall deformation is activated manually. This enables unexpected events in the course of the test to be automatically compensated for and corrected. As soon as the forces acting on the plate have stabilized to a residual value, the rate of traverse is increased to 0.5 mm or 1.0 mm per relieving increment, in order to minimize the test period.

As after relatively few wall movements a constant residual value of the horizontally acting compressive force becomes apparent, the test can be implemented using a “multistep technique”. This means that once this residual value is reached, a higher load is applied, so that a relationship can be established between the vertical load and the horizontal wall movement, from which the safety potential of the structure is derived.

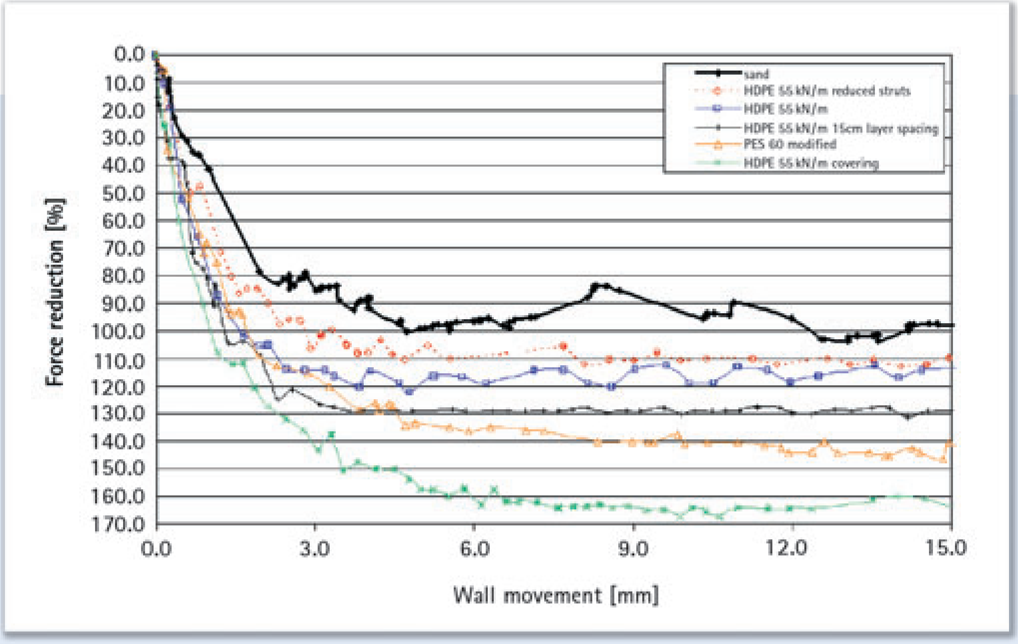


Fig. 11:
Reduction in force [%] compared to the soil without intermediate synthetic layers as the wall movement increases, for different synthetics

Test results

The longitudinal struts of the geosynthetics discharge the load passed into them by friction at the surface. The transverse struts "brace" themselves against the soil lying in the direction of pull and are thus subjected to bending stress. These influences have a different effect on the surrounding soil and overlap. So far there have been too few tests carried out to be able to provide an adequately informed description of this discharge behavior.

It is meaningless to display the results over time for this particular assignment. A relationship should be established between the wall deformation, the vertical loading and the activated strain or tensile forces in the synthetics. In the following representations therefore, the results are given as a function of wall deformation. **Figure 10** shows the reduction in horizontal force as wall deformation increases in a test over the entire height of the biaxial device. A drop in the forces is equivalent to the activation of the transverse forces in the soil structure, that leads to a reduction in the horizontal forces. Initial increases in some of the bolts are explained by force transposition to other areas in the soil structure. As the cylinder has to readjust the load step after each wall movement (see the "control and measuring equipment" section), there are jumps in the recorded values, caused by the reduced vertical loading. These measured values are subsequently sorted, so that **Figures 10** and **11** only contain the measured values that correspond to a uniform loading of 135 kN/m^2 (kPa).

As after a wall movement of approx. 15 mm, a residual friction resistance value became apparent, the lines run virtually horizontally. So to make the crucial area clearer, only the first 15 mm are shown here.

It is quite obvious that at different depths, there are different effects to measure from the decline in horizontally acting stresses. Vertical loading was kept constant throughout the test.

Figure 11, on the other hand, shows the results from five large-scale tests, during which the horizontal force reductions of the six individual measuring bolts were added together, to make them easier to compare with the determined effects. Also recorded here is the reduction in horizontal forces as the wall deformation decreases.

The result from sand with average compaction is also shown as a comparison. It is quite clear that the sand has the typical transverse resistance line of average density sand; there is no distinct peak value and no decline to a residual friction angle.

On the other hand, the other test results show a change in the material behavior of the composite structure. A significantly higher reduction of forces acting horizontally was established for all the synthetics. Peak and residual friction angles can no longer be determined, so that reduced resistance as from a certain deformation is no longer to be expected.

What is conspicuous in the results of the investigations is that there is a clear dependency in the results on the geometry of the synthetics (arrangement of the transverse and longitudinal struts, size of the openings) and the particle size. Whereas in the methods of assessment applied at the time it was solely the axial tensile strength that was regarded as the crucial parameter, this was not determined to be the most significant parameter in the investigations of internal bearing strength. On the contrary, it appears that a geosynthetic with less tensile strength and a more favorable geometry (in each case only for a certain soil particle size) can sometimes discharge far greater forces.

It can also be seen from the results that the resistance to expansion of the synthetics is a crucial parameter, as after only a few wall deformations, a quiescent condition becomes apparent, as the synthetic and the soil form a composite material. With synthetics with greater resistance to expansion, less movement is required and with synthetics with less resistance to expansion more movement is required. The more resistant to expansion the geosynthetics in use are, the greater the forces that can be activated at less deformation.

Additional investigations are currently being planned in order to investigate the stability of the synthetics in the soil composite. Results from the field instrumentations showed that there were only slight signs of creep in the working load range [3].

Summary

The stress/strain behavior of soil reinforced with synthetics cannot yet be described in sufficient detail. To determine the mechanical properties, large-scale tests are implemented in a biaxial device specifically developed for this topic. The forces acting horizontally on a wall are recorded and evaluated with increasing wall deformation. Measuring bolts were developed at the Institut für Geotechnik und Markscheidewesen at the Technische Universität Clausthal for this purpose, to ensure a permanent data record of the forces acting on the wall as wall deformation increases.

Numerous investigations were carried out with the large-scale biaxial device, to make it possible to gain greater understanding of the stress/strain behavior of SRS. A high level of reproducibility was established in the results.

Results show that the vast absorbable force potential of this type of structure is heavily dependent on factors such as the geometry of the synthetics and their resistance to expansion in the initial area. The intermediate synthetic layers significantly reduce the horizontal pressures and deformations whilst simultaneously reducing settlement at the top.

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