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Interaction behaviour of geosynthetics and soil under static and cyclic loadings using the pull-out test

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ABSTRACT: An extensive experimental framework has been evaluated to investigate the static and cyclic interaction behaviour of geosynthetics and soil. Therefore, the development and construction of a new, multifunctional testing device has been carried out to perform large scale static and cyclic pull-out tests. In static tests the grain size distribution, density of the soil, embedment length of the geosynthetics and the vertical surcharge have been identified as core parameters for the maximum pull-out force. “Passive earth resistance” and “interlock” in front of the transverse bars are the prevailing mechanisms of load transference with grid structures. In numerous cyclic model tests the maximum cyclic loading level, the amplitude of the cyclic loading and the number of cycles are identified as core parameters. An improvement of the compound behaviour after application of the cycles due to a “compaction of the soil” and a “cyclic interlock” is monitored. The database is used for the development of a universal methodology to calculate displacements of the structures depending on the amplitude of the cycles and the maximum cyclic loading. A failure criterion is defined to predict a condition of a stable behaviour or a failure of the structure from the displacement-based data. Based on the presented experimental data, a universal concept for the calculation of the anchorage area of cyclic loaded structures is developed which can be implemented into a given concept.

1 INTRODUCTION

When used in reinforced structures or bridging of voids or abutments geosynthetics are exposed to static and cyclic loadings from traffic, machines and construction work. No sufficient knowledge of the interaction behaviour under cyclic loadings is available at the moment.

Therefore, numerous static and cyclic pull-out tests have been performed to evaluate this behaviour.

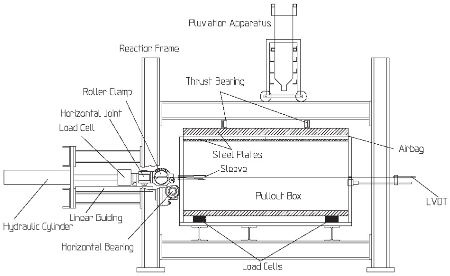

Figure 1. Large scale pull-out testing device.

2 TEST PROCEDURE

The presented study was carried out with a specifically designed, large scale pull-out apparatus at the Institute for Geotechnical Engineering and Mine Surveying at Clausthal University of Technology.

The large scale pull-out apparatus with its internal dimensions of 1.50 m by 0.60 m by 0.60 m (L × W × H) is presented in Figure 1. With this pull-out apparatus static and cyclic loadings are applied in the horizontal axis (axis of the test specimen) and in the vertical axis. Cyclic loads can be applied in the horizontal direction with frequencies of up to 4 Hertz by a hydraulic system in a load-controlled mode.

First, a displacement-controlled mode is performed until a maximum load level F_o of the cycles is reached. Then, horizontal load cycles with an amplitude of ($F_o - F_u$) are applied. This procedure insures tests at realistic loading levels (Figure 2).

While keeping a constant maximum loading level F_o, test series are carried out with different minimum loading levels F_u and therefore different magnitudes

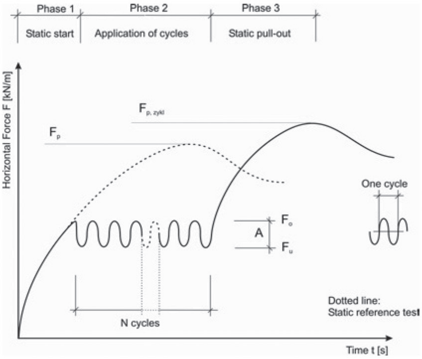

Figure 2. Cyclic testing procedure.

of amplitudes. Additionally, series of tests with a variation of F_0 are performed in which different static loadings (dead weight of the soil) are combined with variable cyclic loadings (traffic). This loading environment represents the conditions which are found in the anchorage areas of reinforced structures.

Finally, a displacement-controlled phase is carried out to evaluate the change of the maximum pull-out force due to the cyclic components (phase 3).

For detailed information about the test device and the testing procedure refer to Meyer et al. (2004) or Nernheim and Meyer (2004).

3 STATIC TEST RESULTS

In static tests the grain size distribution, density of the soil, embedment length of the geosynthetic and the vertical surcharge have been identified as core parameters for the maximum pull-out force. “Passive earth resistance” and “interlock” in front of the transverse bars are the prevailing mechanisms of load transference with grid structures. Figure 3 shows that the removal of 75% of transverse bars results in a reduction of about 50% in the maximum horizontal force compared to the case where all transverse members are present.

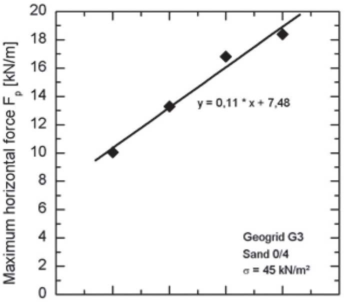

Figure 3. Effect of the transverse bars on the Pull-Out behaviour.

4 CYCLIC TEST RESULTS

Additionally, horizontal loading level, horizontal load amplitude and the frequency of loading are varied in the cyclic test framework. Cyclic test results are analyzed depending on the measured displacements of the geosynthetic material during the cyclic phase 2 shown in Figure 2.

Different materials show different developments of cyclic displacements (Figure 4). Displacements are very small for the smooth steel strip but a potential failure occurs without any prior warning. With the geogrid the displacement level is higher and no hazardous potential pull-out failure can be monitored. Therefore, a distinct failure criterion is difficult to determine.

Test results show that the frequency has no significant influence on the development of displacements in a range of 0,1 to 2.5 Hz. This is in accordance to Raju and Fannin (1997). However, the measured cyclic displacements in phase 2 of the test increase significantly with increasing amplitude or loading level. Therefore, an analytic relationship has been evaluated which describes cyclic displacements

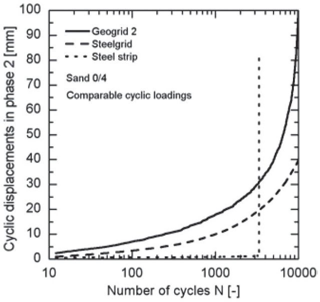

Figure 4. Development of cyclic displacements for different reinforcement products.

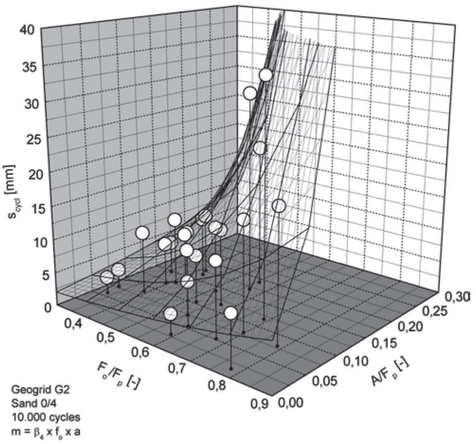

Figure 5. Calculated and measured cyclic displacements with different amplitudes and loading levels.

for different geogrids and soils depending on these core parameters. This regression analysis leads to the displacement levels shown in Figure 5, which match well with the measured values. Forces have been normalized to the maximum static pull-out force F_p in this chart for easier comparison of different geosynthetics and soils.

If displacements of phases 1 and 2 of the test procedure shown in Figure 2 are combined an estimation of the complete displacements due to the simulated installation of the geogrid product and traffic loadings can be performed. Formula 1 shows the calculation with α_i (i = 1, 2, 3) being regression constants for the static part, β_i (i = 1, 2, 3) being regression constants for the cyclic part, f_o (= F_o/F_p) the normalized loading level and a (= A/F_o) the normalized amplitude. The graph shown in Figure 6 indicates a good agreement of calculated and measured values.

$$s_{start+cycl} = \left(e^{\frac{\alpha_1 f_o}{\alpha_2}} - \alpha_3 \right) \cdot s_p + \beta_1 \cdot e^{\beta_2 \cdot f_o + \beta_3 \cdot a + m}$$

Formula 1. Calculation of total displacements from phases 1 and 2 in dependence of loading level f_o and amplitude a.

Because these calculated displacements depend on the geosynthetic and soil-type, a static reference test and a number of time-consuming and costly cyclic tests have to be performed. To avoid this, simplified equations have been developed for a rough estimation of the displacments (Nernheim, 2005).

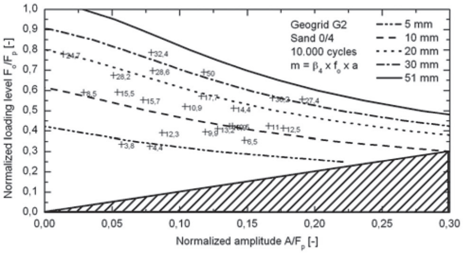

Figure 6. Total displacements of phase 1 and 2 with geogrid G2 at 10.000 cycles.

5 DISCUSSION AND ANALYSIS

The presented results only show the displacements produced by the cyclic loadings which is an important information for the serviceabilty limit state. Up to now, no statement can be given on the ultimate limit state.

A suggestion for a modified failure criterion based on the combined displacements of phases 1 and 2 of the cyclic model test is proposed. The combinded displacements will be compared with the peak displacement s_p (displacement of the geosynthetic corresponding F_p) of the associated static reference test (Figure 7). Using this variable criterion instead of a fixed value, the impact of the displacement on the system which depends on the geosynthetics, the soil and the vertical overburden is taken into account.

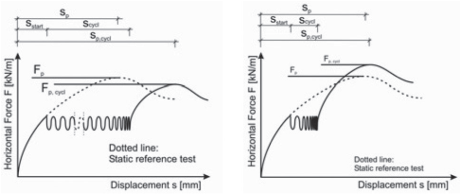

Figure 7. Failure criterion to evaluate whether a test is unstable (left) or stable (right) for a given number of cycles.

According to Formula 2, an unstable behaviour of the specimen for a given number of cycles is identified, if the combined cyclic displacements from phases 1 and 2 are larger than the displacement s_p from the associated static reference test. Smaller values in the cyclic test lead to a stable behaviour (Formula 3).

$s_{start} + s_{cycl} > s_p$ Formula 2

$s_{start} + s_{cycl} < s_p$ Formula 3

If the presented failure criterion is applied to every cyclic test, a stable or an unstable behaviour of the compound geosynthetic-soil system can be evaluated at any given number of cycles. An analysis of the test results obtained for 10.000 cycles is presented in Figure 8 for three different geogrids and a steel grid in one type of sand and one type of gravel. Grid 3 has been evaluated with 100% and 50% transverse members, as they account for a large percentage of load transference from the grid into the soil (Figure 4).

A stable area can be detected at small loading levels and small amplitudes. If these parameters are increased, the "changing zone" to an unstable behaviour is reached. Because of the different materials and data scattering, this band can be reduced to a single line which is called "line of failure". It can be concluded that by using data normalization tests with different geosynthetics or soils can be combined in a single chart. At higher amplitudes slight differences can be monitored between the behaviour of geogrids in sand 0/4 (Figure 8).

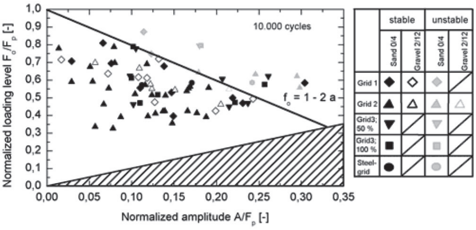

Figure 8. Interpretation of the failure behaviour with different kinds of soil and different geosynthetics at 10.000 cycles

With the help of this "line of failure" a method is developed to calculate an optimal embedment length l_{opt} for every vertical surcharge (correlating to the actual depth of the reinforcement layer in the reinforced structure). This embedment length must guarantee that the compound system withstands the cyclic loading conditions without any detractions of the load transference mechanisms. The maximum static pull-out force $F_{p,cycl}$ after application of the cycles should be at least in the dimension of F_p (Figure 2). This iterative procedure can be called "cyclic pull-out design".

For every layer in a reinforced structure, it has to be checked, whether the embedment length obtained from the static design or from the presented cyclic design is the dominant parameter.

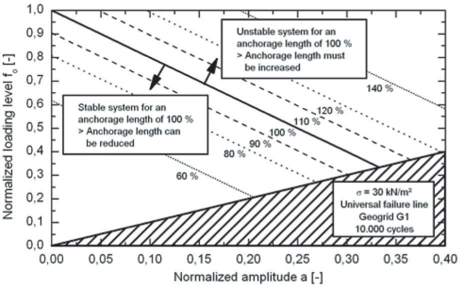

Figure 9. Example of a chart used to determine the optimal cyclic anchorage length; the chart is created by applying the failure criterion on the cyclic tests.

For different vertical surcharges and interaction conditions, charts have been developed from the test results, which can be used to calculate this embedment length l_{opt} without requiring an extensive test program. Starting from a given vertical surcharge σ and a reference embedment length $l_{100\%}$ the optimal embedment length l_{opt} can be derived as percentage of the reference embedment length of Figure 9 for a predetermined cyclic loading in this layer of the structure.

6 CONCLUSION

A large scale pull-out test device for static and cyclic tests and a procedure for performing cyclic pull-out tests are presented. The type of geosynthetics, type of soil, loading level and amplitude have been extracted as core parameters influencing the displacements in the cyclic test phase. An analytical equation to calculate these displacements is derived. A displacement-dependent failure criterion leads to a design method which can be used to evaluate a "cyclic embedment length" l_{opt} that depends on the vertical surcharge and the interaction parameter. With this tool, a combined static and cyclic anchorage design can be performed.

In the future, additional soils with a wide range of grain sizes will be tested because of their significant influence to the load transferring. Furthermore, systematic in-air-tests of geosynthetics under cyclic loadings should be performed to evaluate the influences on these materials, and, finally, more detailed data on the traffic-induced cyclic loading affects on reinforcement layers is required.

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