The load case "Execution Phase" of stratified geosynthetic systems

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ABSTRACT: This contribution considers in detail the proof of efficiency of stratified capping sealing systems during the execution phase and rates the commonly used proving methods. Incorrect assessments will be shown and an alternative assessment will be presented giving the applied formula. Using the presented assessment, the marginal conditions during installation can be optimized to avoid local overloads by considering the construction device data and the layer thickness of the cover soil. With respect to the shown significant faults of frequently used design assessments an urgent need for change is stated and should be discussed.

1 INTRODUCTION

Due to their economy -among other advantages- stratified geosynthetic systems have become generally accepted in landfill construction, hydraulic engineering and groundwater protection during the past decades. High production standard and quality control provide long-term stability of these construction materials which can be compared to those used in conventional construction. The faultless installation of the stratified geosynthetic systems is absolutely necessary. With respect to project specific conditions the stability of the systems has to be proved both for the final situation after construction and during the "execution phase". In general practice, the load case "execution phase" has frequently been neglected compared to the load case "final situation". One reason for this may be the multitude of loads to be considered, the dimensions and interaction of which are normally not known in advance.

Only after the first problems concerning the stability during the installation process occurred -the possible slope inclination in correlation with the contact friction angles of the geosynthetic layers and the loads resulting from used construction devices came up against their limiting factors- the stability during the execution phase was examined in detail.

Unfortunately, the available standards or recommendations do not provide sufficient instructions for a differentiated design of stratified systems. Although the EBGEO (1997), for instance, which is commonly used in Germany is considering the load case execution phase, the bases of the presented assessments are already wrong and lead to misunderstandings. On the international level, the load case execution phase is not taken into consideration, compare GLR (1993) and Koerner (1997). Paruvakat/Richardson (1999) only consider shear forces occurring during the execution phase which can be derived from the earth static point of view.

In the authors' opinion a design assessment, however, has to include the actual marginal conditions -and thus also dynamic influences resulting from the execution process- and it has to allow differentiated statements regarding the stability by using a comprehensible model.

The basic considerations of this contribution were first published in German in 1999 by Broers/Saathoff. Since the German version found positive acceptance in professional circles, the basic thoughts will be presented to international experts in the following.

2 STABILITY OF CAPPING SEALING SYSTEMS

Carried out stability analysis' of capping sealing systems lead to surprising results. In many cases it is not the final situation that has to be assessed critically but the execution phase, due to additional static and dynamic loads resulting from construction devices / on-site vehicles driving on the cover soil. As a consequence a stable cover in the final situation needs a reinforcing element in the execution phase or the execution process has to be optimized.

The loads applied to a sealing system resulting from on-site vehicles are more significant than considered in general practice, also under the aspect of the applied shear stresses and the resulting displacement of the sealing system.

Due to the fact that the cover soil has been installed before the sealing system is passed over, a local overload of the system will rarely be seen directly. A failure with resulting sliding of the construction device and elements of the sealing system indicating insufficient stability cannot be accepted. With respect to quality control, loads transferred to the sealing components or displacement of individual elements have to be avoided particularly for capping sealing systems in landfill construction. A sufficient safety coefficient in the stability analysis can be useful in this connection and provide reference values.

3 DESIGN

3.1 *Final situation*

To evaluate the stability of stratified systems the characteristic contact friction angle and/or the shear resistance of the critical layer interface have to be deduced from the stratified system consisting of geosynthetics and earth materials. Based on the characteristic values of this layer interface parallel to the slope the resisting and driving forces working in down slope direction have to be compared.

The ratio between the resisting and driving forces reflects the achieved level of stability. According to DIN 4084 valid in Germany, the load case execution phase requires a safety coefficient of $\eta \geq 1.2$, the load case "final situation" requires a safety coefficient of $\eta \geq 1.3$.

To determine the stability in the final situation multiple conditions have to be taken into consideration, for example:

- slope inclination
- slope length
- layer thickness of the cover soil
- decisive contact friction angles of all layer interfaces
- internal shear resistance of the soils and geosynthetics under consideration of the long-term shear resistance
- flow forces resulting from drainage
- if necessary, loads resulting from wind or snow.
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3.2 *Execution phase*

It is more difficult to list the loads resulting from the execution process. When the sealing system is passed over after the cover soil has been installed in a defined final thickness d or of partial layer thickness' d_i during installation, both static forces resulting from the weight of the on-site vehicles and dynamic forces resulting from its direct movement will affect the system.

The correct assessment for the calculation of the dynamic loads can surely be discussed controversially. Considering the multitude of construction devices actually used in landfill construction and their specific loads, a complete listing and consideration of these differences has to be aimed at. From the authors' point of view, the assessment of an overall "motion coefficient" for all vehicle groups -this assessment can be found in EBGEO- cannot guarantee an optimum result.

On the contrary, the following data are characteristic for on-site vehicles in any case:
- the individual weight
- the dimensions, particularly those of the contact area of the construction device towards the soil
- velocity and
- braking retardation.

The mentioned conditions can only lead to satisfying results when they are interacting properly. The BBG assessment described in the following connects the conditions from geometry, sealing system and loads resulting from the execution process, as far as these data could be determined in practice.

4 BBG ASSESSMENT FOR STABILITY ANALYSIS

4.1 *Marginal conditions*

The loads which have to be determined and which result from driving on the sealing systems (resisting, driving and dynamic forces) are projected to the level of the sealing system or, if necessary, to a critical area by means of a load distribution angle depending on the layer thickness of the cover soil. The loads per square metre occurring during the execution phase which have to be assessed for the calculation will thus be lower than those soil compression values given by the on-site vehicle manufacturers.

The shear forces transferred into the system by traffic (Fig. 1) are transmissed both by the friction in the layer interfaces and, possibly, by supporting the cover soil towards soil already installed.

The second aspect, however, is not applicable for low thickness or low compression of the cover soil. Even in case of higher thickness' of the cover soil, higher displacements are necessary to build up an appreciable passive earth pressure when a low compression is given. This already may cause overloads in the stratified geosynthetic system which result in visible damage afterwards. Normally, the effect of a "support abutment" thus cannot be applied for the construction phase.

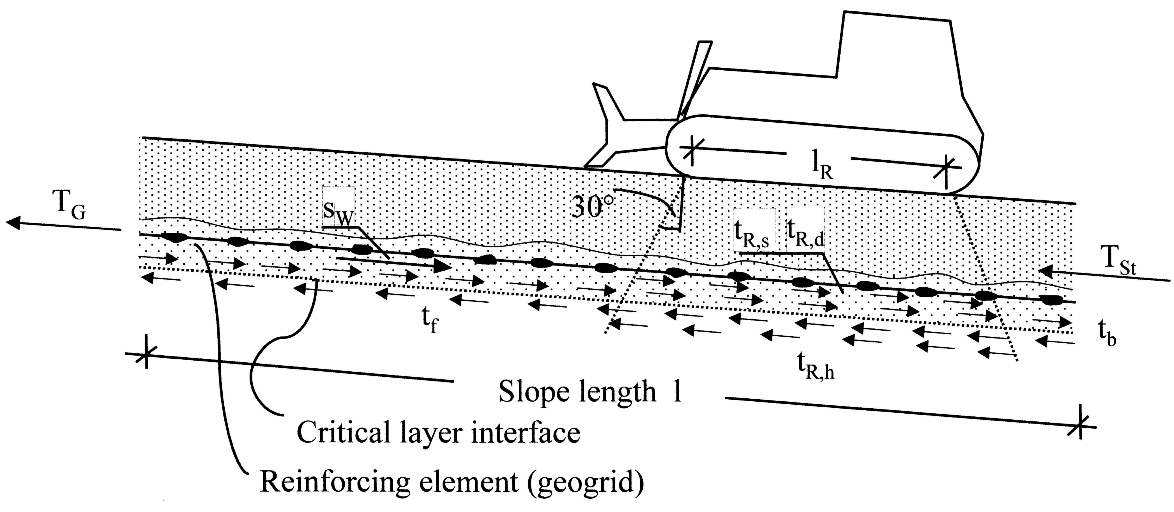

Figure 1: Shear forces occuring during construction (used abbreviations see chapter 5.1)

4.2 *Assessment of the construction device / on-site vehicle*

The loads actually transferred into the sealing system resulting from the construction device / on-site vehicle consist both of static and dynamic components. Load components resulting from the on-site vehicle have effects, both on the layer interface normal to the slope direction as well as in down slope direction (static components). In the first case an increase of the friction in the layer interfaces will result in "resisting" forces, in the second case in "driving" forces.

Compared to this, the loads which result from a braking retardation of the on-site vehicle and which in most cases run in parallel direction to the slope -having an unfavourable effect in down slope driving direction- only have "driving" effects (dynamic component).

The following example should be considered:

- use of a track-type caterpillar to install the vegetation layer / cover soil
- slope inclination $\beta = 20°$
- friction angle of the critical interface cal $\delta = 27°$
- (in the execution phase) driving on the slope with a simple track-type caterpillar with a usual total weight of approx. $G_R = 13$ t
- data of the on-site-vehicle:
  length of chain track $l_R = 2.7$ m;
  width of the chain track $b_R = 0.9$ m;
  maximum velocity $v = 2.8$ m/s;
  time required until the on-site vehicle stands still $t = 1.4$ s
- installation of cover soil by selected layer thickness d_i in steps by 0.5 m up to a total thickness d of 2.0 m.

The length of the slope is variable (at maximum 30 m).

The result is the safety coefficient η in the execution phase depending on the length of the slope l and the thickness d_i of the cover soil.

Figure 2 shows that even in case of a simple track-type caterpillar considerably lower safety coefficients for a shorter slope length are determined when the BBG assessment of the construction device with static and dynamic load components is used, compared to the assessment of a "motion coefficient".

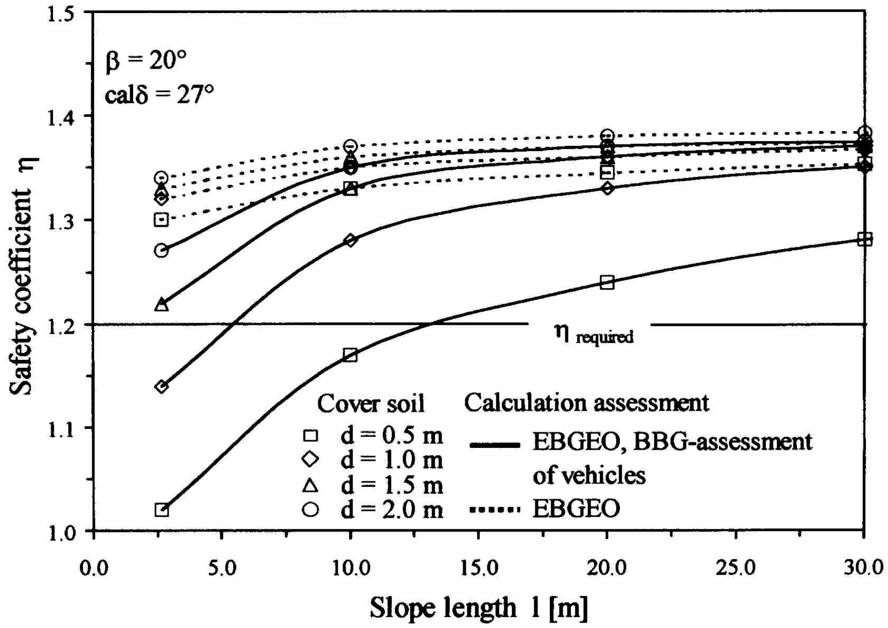

Figure 2: Comparison of stability calculation of a slope by using different assessments for the construction device

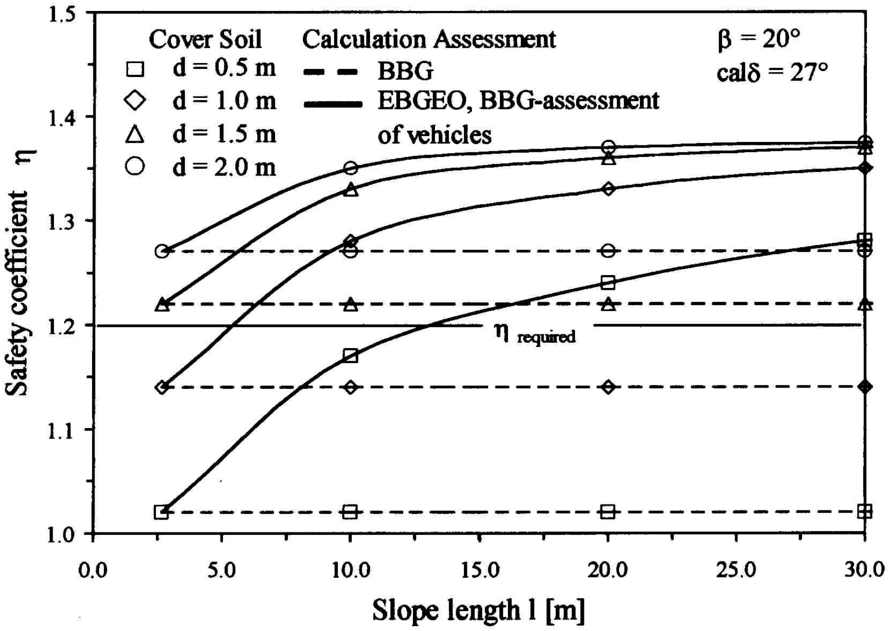

Figure 3: Comparison of stability calculations of a slope for different decisive slope lengths

Based on a comparison between the driving force of the on-site-vehicle, which is constant, and a part which increases linear with an increasing slope length, resulting from the mobilized friction in the shear interface, an asymptotic approximation of the calculated static safety coefficient to a constant level can be achieved. The difference in the calculation approach for the on-site vehicle has a significant effect in cases of short slopes.

The influence of the thickness of the cover soil that is passed over by on-site vehicles becomes evident as well: The thicker the layer, the more favourable the load distribution and thus the share of the driving dynamic forces.

To sum up: The example shows that in accordance to the BBG assessment the consideration of the on-site vehicle data and the layer thickness' leads under specific conditions to insufficient stability (e.g. layer thickness of the cover soil $d_1 = 0.5$ m and slope length $l = 10$ m). Using the same values with commonly used calculation assessments a sufficient stability is calculated.

4.3 *Introduction of the limit state value κ*

Apart from discussing the design assessment of the construction device (on-site vehicle) the basic question has to be debated in how far locally restricted stresses of a sealing system caused by on-site vehicles can be compensated by possibly favourable marginal conditions which result from the total situation of a slope (e.g. a gentle inclination or a good bond shear behaviour within the layer interfaces). Due to the reasons described in chapter 4.1, the authors opinion is that there is no doubt that forces which are locally transferred into a sealing system by a construction device can be compensated by resisting friction forces integrated over a long slope. First of all, the "floe / clod" which is affected by the on-site vehicle has to be evaluated independent of the total slope. In continuation of the calculation results shown as examples in Figure 2, the situation shown in Figure 3 is achieved.

Shown in Figure 3, as a comparison, are the results from Figure 2 of the BBG assessment for the on-site vehicle (asymptotic approximation of the achieved safety coefficient to a constant value). In comparison to this, the calculation results of the BBG assessment (see chapter 5) are shown.

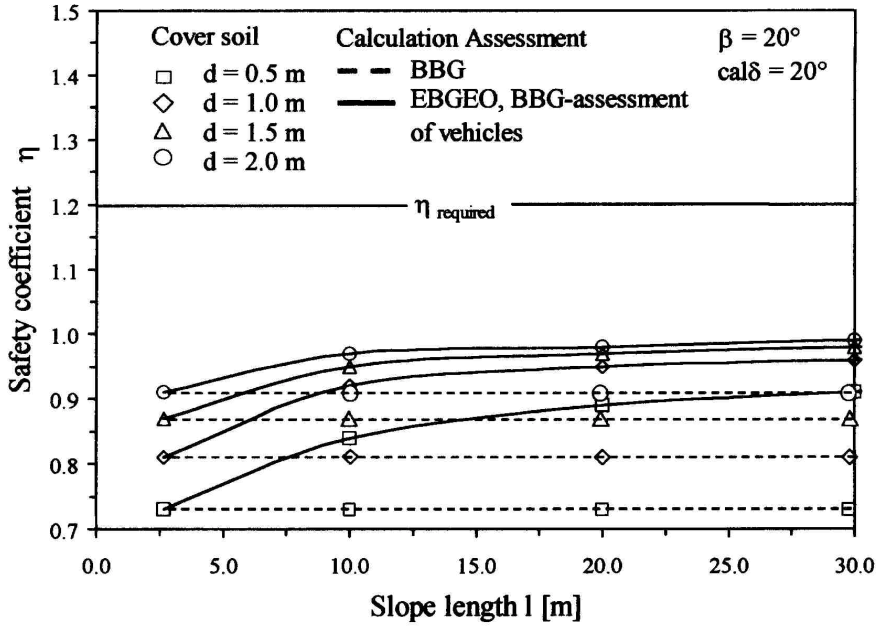

Figure 4: Safety coefficient for decisive slope length of a not stable slope

In case of the chosen slope example, passed over by a light track-type caterpillar of approx. 13 tons, a constant safety coefficient is achieved independent of the position of the on-site vehicle on the slope since only the length of the vehicle is a factor in the calculation and not the total slope length.

Under marginal conditions which are the same in other respects a different result can be found for the above shown calculation results as soon as a lower contact friction angle, e.g. cal $\delta = 20°$ instead of 27° is taken as a factor (Fig. 4).

In this case the stability of all considered slope lengths is lower than the required stability of $\eta \geq 1.2$. With an increasing slope length the stability safety coefficient approximates to a constant value. The fundamental difference of a slope, which is substantial stable, neglecting the influences of the on-site vehicle (Fig. 3, $\delta = 27°$), and a slope, which over all areas shows no sufficient stability (Fig. 4, $\delta = 20°$) results from the consideration of deficit forces, as shown below.

The result makes it necessary to differentiate between two cases: $\kappa < 1.2$ and $\kappa \geq 1.2$ (Fig. 5 and Fig. 6).

4.3.1 *$\kappa < 1.2$*

If a slope cannot be regarded as stable due to insufficient friction coefficients within the stratified system (that means the required safety coefficient of 1.2 in the execution phase is already achieved without traffic) a reinforcement element (geogrid) has to be installed which transmits the deficit forces integrated over the slope length at the slope crest. Traffic during the execution phase results in a higher load. The amount of the additional driving dynamic forces of the on-site vehicle has to be added to the maximum deficit force at the slope crest (Fig. 5).

The limit state of a sufficient stability during the execution phase without traffic will be defined as ratio in limit state κ [-] in the following.

In addition to the results shown in Figure 4, Figure 7 shows the required tensile forces to be absorbed in an anchor trench on the slope crest as a function of the slope length. In this case the ratio has been calculated to $\kappa = 0.99$.

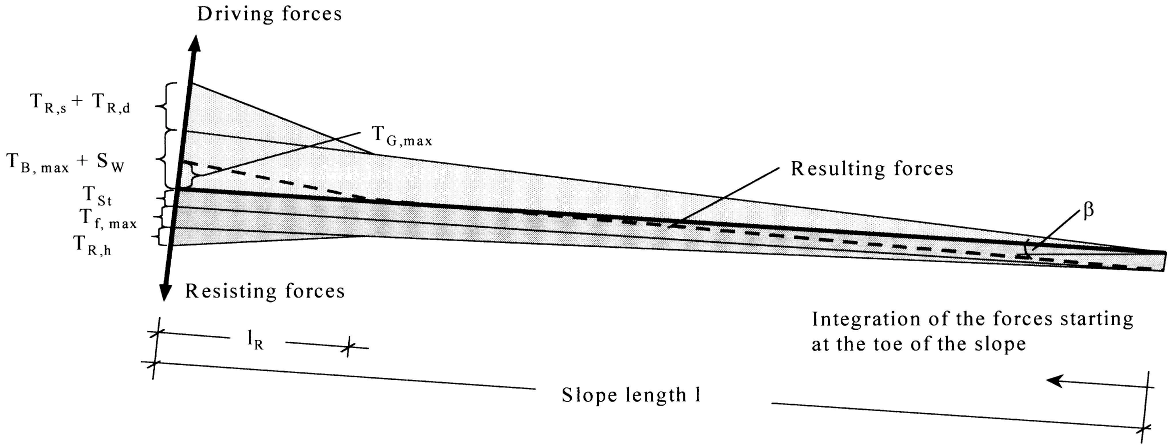

Figure 5: Integration of the forces over the slope length at a ratio κ < 1.2
(used abbreviations see chapter 5.1)

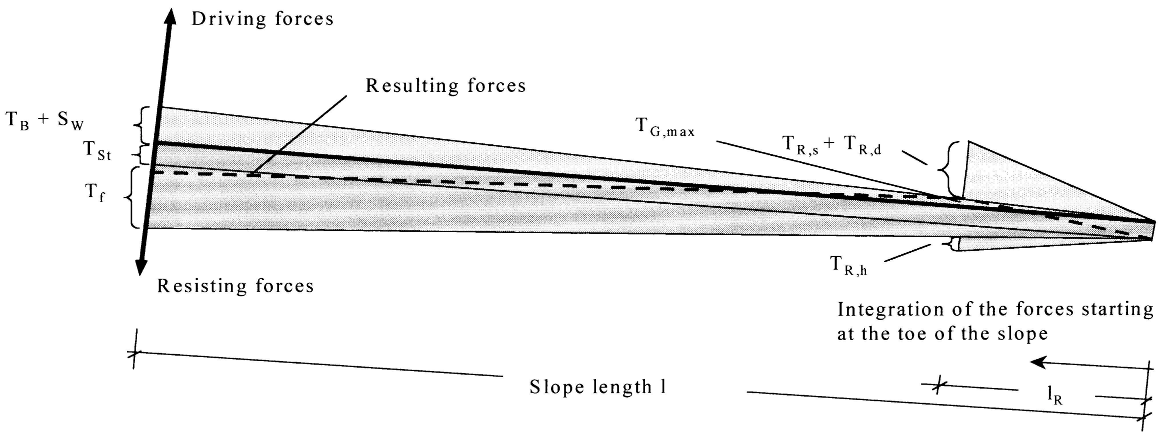

Figure 6: Integration of the forces over the slope length at a ratio κ ≥ 1.2
(used abbreviations see chapter 5.1)

4.3.2 *κ ≥ 1.2*

Contrary to the above described case κ < 1.2 it is not necessary to reinforce a slope when the slope reaches the limit state value of κ ≥ 1.2 as a result of the geometric marginal conditions in consideration of the decisive contact friction angle (Fig. 6).

Under disadvantageous marginal conditions -which are frequent in practice- the local stability is not reached in the area directly influenced by traffic, particularly when the cover soil layers on top of a sealing system are thin (compare Fig. 3 and Fig. 4). In this case, the installation of a geogrid is indispensable to compensate local instabilities during the execution phase or alternatively the installation conditions can be varied (different on-site vehicle, optimized friction behaviour of the sealing system etc.).

4.4 *Optimizing possibilities*

The BBG assessment allows a differentiated consideration based on project specific data. In case of the example assessment, Figure 3 shows that the achieved safety coefficient is increased (compared with the required safety coefficient) by approx. 10 % when the thickness of the layer on which the

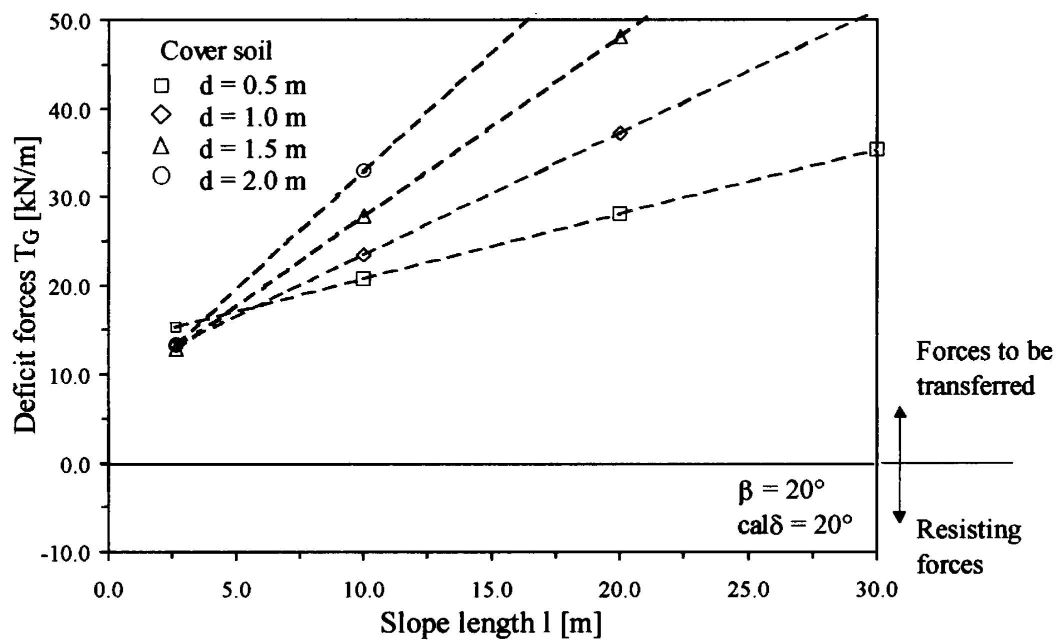

Figure 7: Required tensile forces T_G for the calculation results shown in Fig. 4 ($\kappa < 1.2$)

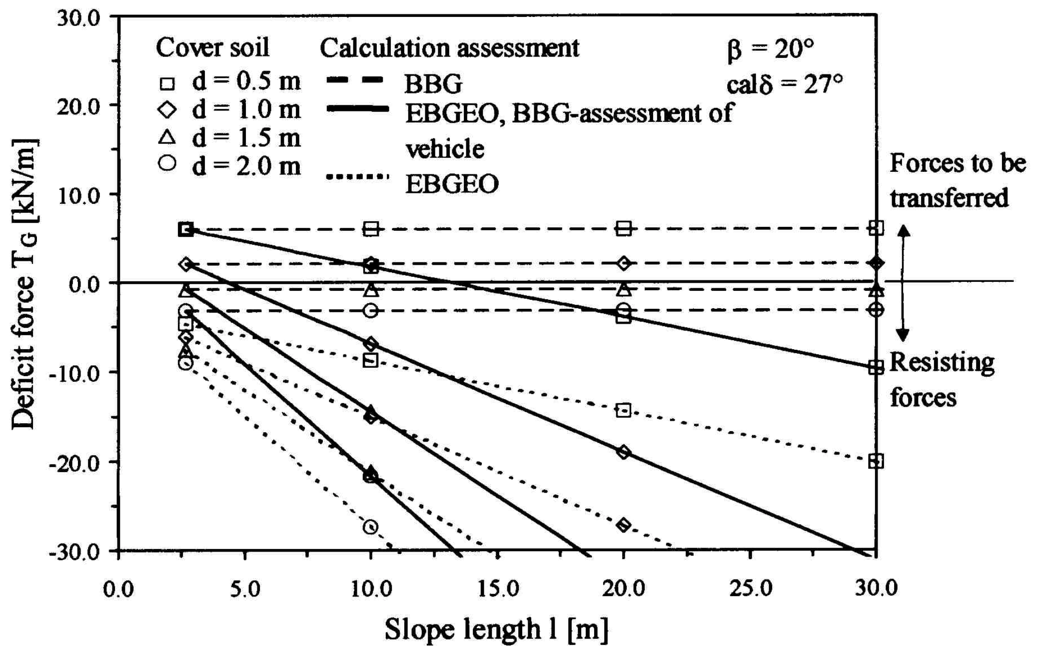

Figure 8: Required tensile force given by different calculation assessments ($\kappa \geq 1.2$)

first traffic on top of the sealing system occurs is raised from 0.5 m to 1.0 m. This result is even more evident for the required tensile strength of the geogrid (Fig. 8).

When the layer thickness is raised from 0.5 m to 1.0 m a tensile strength of only 2 kN is required instead of 6.5 kN. It may be that this amount can be attributed to an adhesion component in the critical layer interface which otherwise is neglected and the installation of a geogrid is not necessary.

As a comparison: Calculating in accordance to EBGEO for a slope length of l = 20 m a resisting force of 27.2 kN/m is shown in Figure 8. In opposite to this a calculation following the BBG assessment leads to deficit forces of 6.5 kN/m at maximum. In the end the EGBEO assessment suggests a level of safety that is not given (compare Fig. 3).

When the BBG assessment is used further optimizing possibilities result from the adaptation of the allowed velocity of the vehicle, a more favourable load distribution by using wider tracks or a lower weight.

With low expenditures and -in most cases- without additional costs the execution phase of a specific project can be optimized to grant the stability according to quality control aspects by involving the participating enterprises and construction companies.

5 FORMULARY TO THE BBG ASSESSMENT

5.1 *Signs*

A	effective contact area of the caterpillar under consideration of the load distribution (m²)
a_v	braking retardation (m/s²)
a'	adhesion of the decisive contact interface (kN/m²)
b_R	width of the caterpillar track (m)
d	thickness of the vegetation layer (m)
d_d	thickness of the drainage layer (m)
d_i	selected layer thickness for traffic on top of the sealing system (m)
G_R	dead load of the on-site vehicle (kN)
g	acceleration due to gravity (10 m/s²)
h_S	height of the support abutment (m)
h_W	medium head of water (m)
K_p	passive earth pressure coefficient (-)
l	slope length (m)
l_R	length of on-site vehicle corresponding to the length of the caterpillar track (m)
s_W	forces due to seepage (kN/m²)
S_W	maximum value of the driving forces due to seepage summarized over the slope length (kN/m)
T_B	maximum value of the shear forces resulting from the dead load of the cover soil in down slope direction summarized over the slope length (kN/m)
T_f	maximum value of the mobilized friction force in the critical shear plane summarized over the slope length (kN/m)
T_G	required tensile strength of a reinforcing element (kN/m)
$T_{R,d}$	maximum value of the driving forces resulting from a full braking of the vehicle (dynamic load), summarized over the length l_R (kN/m)
$T_{R,h}$	maximum value of the friction forces resulting from the dead load of the vehicle, summarized over the length l_R (kN/m)
$T_{R,s}$	maximum value of the driving forces resulting from the dead load of the vehicle in down slope direction, summarized over the length l_R (kN/m)
T_{St}	supporting force given by a passive earth pressure at the toe of the slope (kN/m)
t	time required until the on-site vehicle stands still (s)
t_B	driving force in down slope direction resulting from the dead load of the cover soil (kN/m²)

t_f mobilized friction force in the critical shear plane (kN/m²)
$t_{R,d}$ driving force resulting from a full braking of the vehicle (kN/m²)
$t_{R,h}$ additional friction force from the dead load of the vehicle (kN/m²)
$t_{R,s}$ driving force from the dead load of the vehicle (kN/m²)
v maximum velocity of the on-site vehicle (m/s)
β slope inclination (°)
κ limit state value (-)
δ' friction angle of the decisive contact area (°)
γ unit weight of the soil (kN/m³)
γ_W unit weight of water (10 kN/m³)
η safety coefficient (-)

5.2 *Driving forces*

Shear force t_B
The shear force t_B per running metre slope length in down slope direction resulting from the dead load of the cover soil can be calculated:

$$t_B = \gamma \bullet d_i \bullet \sin\beta \quad (1)$$

Seepage s_w
After heavy rain fall the water can be retained in the drainage layer of the capping sealing system. The resulting additional driving forces are defined as seepage. To determine the seepage it is necessary to assess the retained water quantity in the drainage layer. For preliminary design the seepage can be assumed to $h_W \approx d_d/2$. The seepage per running metre slope length is calculated:

$$s_W = \gamma_W \bullet \sin\beta \bullet h_W \quad (2)$$

Additional shear forces $t_{R,s}$ and $t_{R,d}$ in the execution phase
When the slopes are very long it can be assumed that the soil material will be installed by using caterpillars. As a consequence additional shear forces which have to be transferred will appear in the critical interface. These forces are composed of static components ($t_{R,s}$) and dynamic components ($t_{R,d}$).

Shear force $t_{R,s}$ resulting from static load
The shear force in down slope direction caused by the individual weight of an on-site vehicle is resulting from:

$$t_{R,s} = G_R \bullet \sin\beta / A \quad (3)$$

According to DIN 1072 a load distribution angle of 30° may be chosen. The result in the effective contact area A is:

$$A = 2 \bullet l_R \bullet b_R + 4 \bullet l_R \bullet d_i \bullet \tan 30° \quad (3.1)$$

Shear force $t_{R,d}$ resulting from dynamic load
The shear forces in parallel direction to the slope caused by a full braking of the vehicle are resulting according to equation 4:

$$t_{R,d} = (G_R / g) \bullet a_v / A \quad (4)$$

The braking retardation is resulting from:

$$a_v = v / t \quad (4.1)$$

5.3 *Resisting forces*

Friction force t_f
The effective friction force t_f in the critical shear interface caused by the load of the cover soil per running metre slope length is resulting on the basis of equation 1:

$$t_f = \gamma \bullet d_i \bullet \cos\beta \bullet \tan\delta' + a' \qquad (5)$$

To be on the safe side, the adhesion a' will not be taken into account in most cases (a' = 0).

Supporting force T_{st} at the toe of slope
For short slopes and well compacted high layer thickness' of the cover soil, it may be possible to involve a supporting force T_{St} resulting from the passive earth pressure of the installed soil at the toe of the slope:

$$T_{St} = 0.5 \bullet \gamma \bullet h_S^2 \bullet K_p \bullet \cos\beta \qquad (6)$$

Additional friction force $t_{R,h}$ resulting from the dead load of the construction device / on-site vehicle
The resisting force from the weight of the vehicle is resulting in analogy to equation 3:

$$t_{R,h} = G_R \bullet \cos\beta \bullet \tan\delta' / A \qquad (7)$$

5.4 *Determination of the ratio value in the limit state*

$$\kappa = (t_f \bullet l + T_G + T_{St}) / (t_B \bullet l + s_w \bullet l) \qquad (8)$$

For the first design step the required force of a reinforcing element T_G, needed to get a satisfactory safety coefficient for the slope stability, can be assumed to zero.

As described in chapter 4.1, a supporting force T_{St} at the toe of the slope can not be taken into consideration when the cover soil is installed from the top to the toe of the slope or at greater slope length. Following this in most cases T_{St} has to be set to zero also:

$$\kappa = t_f / (t_B + s_w) \qquad (8.1)$$

5.5 *Determination of the safety coefficient η*

Depending on the determined κ equation 9 or equation 10 is getting decisive. If the required safety factor η can not be satisfied, equation 9 respectively equation 10 has to be shifted to T_G and the required force of a reinforcing element can be determined.

Stability for $\kappa < 1.2$

$$\eta = (t_f \bullet l + t_{R,h} \bullet l_R + T_G + T_{St}) / [(t_B + s_w) \bullet l + (t_{R,s} + t_{R,d}) \bullet l_R] \qquad (9)$$

Stability for $\kappa \geq 1.2$

$$\eta = (t_f \bullet l_R + t_{R,h} \bullet l_R + T_G + T_{St}) / [(t_B + s_w + t_{R,s} + t_{R,d}) \bullet l_R] \qquad (10)$$

6 SUMMARY

The present contribution considers in detail the analysis of efficiency of stratified capping sealing systems in the execution phase and evaluates the commonly used practice of stability analysis. Wrong assessments are made evident and an alternative assessment is introduced including the formulary.

The assessment presented by BBG Bauberatung Geokunststoffe GmbH & Co. KG allows a practice related design in consideration of project specific marginal conditions, particularly in case of traffic on top of the capping sealing system. The model results clearly show that the decisive slope length requires the differentiation of two cases to determine the stability and the design strength of a possibly required reinforcing element. The first case results in a summation of deficit forces over the slope length and an addition of the extra load resulting from on-site vehicles. The second case considers a locally limited area directly influenced by the construction device for design. A ratio value in the limit state κ is defined to differentiate the two cases.

The introduced assessment makes it possible to optimize the marginal execution conditions by involving the vehicle data and the layer thickness of the cover soil to avoid local overloads. With respect to the detected significant imperfections of frequently used assessments an urgent need for change is stated and discussion is suggested.

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