Comparison of Different National Guidelines and Standards regarding the Design of Soil Retaining Walls with Extensible Reinforcements

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Abstract:

Soil reinforced walls are a type of retaining walls that does not have a specific way of calculating yet, as different methods for calculation exist. External stability is calculated mostly the same way in each country, while internal stability has different calculations methods in different countries. The USA uses the Simplified Method, the UK and France the Tieback Wedge method and in Germany just a wedge stability check is performed. However, it is not clear which guidelines, and as such which calculation methods are more conservative than the other. A design in the Ultimate Limit State of a simple reinforced soil wall with a traffic surcharge and extensible reinforcement has been performed, following four different countries guidelines (USA, UK, France and Germany). Afterwards performance ratios are calculated for sliding on the base, bearing on foundation, rupture and pull-out. It became clear that the biggest differences in performance ratios were because of different calculation methods and that the partial factors only had a very small role to play, except for sliding on the base. As well as that the German guideline does not calculate the maximum tensile force in each layer, opposite to the other three guidelines. Furthermore Serviceability Limit State is mentioned in all four guidelines but no in-depth explanation nor equations were given in each of the guidelines.

1 Introduction

Reinforced soil structures are both economically and technically very advantageous over their conventional counterparts, especially under poor soil conditions, and also when there are space and property line limitations. Moreover, reinforced soil structures provide numerous other indirect savings and conveniences, such as speedy construction time, ease in construction methods, graceful appearances, etc [1].

2 External stability

The USA guideline [2], the UK guideline [3] and French guideline [4] all make the same assumptions about the acting forces on the reinforced soil block, with a horizontal backslope with traffic surcharge, Figure 1.

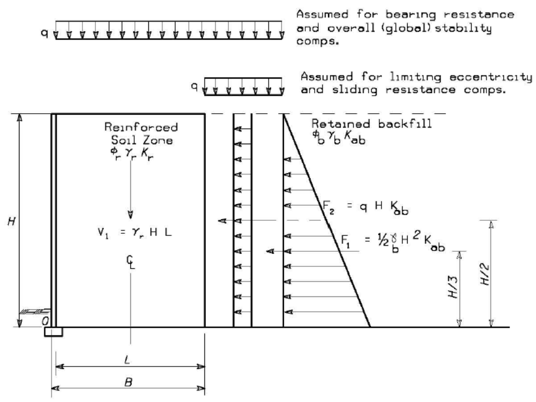

Figure 1: Nominal earth pressures, USA, UK, France [2]

The German guideline [5] assumes that the earth pressure does not only act horizontally but vertically as well, Figure 2.

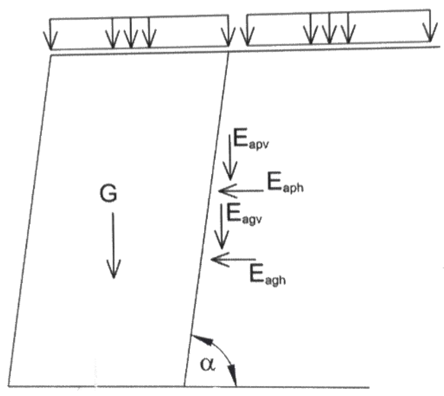

Figure 2: Nominal earth pressures, Germany [5]

Sliding on the base

The sliding force is calculated the same way in each country by taking the sum of the horizontally acting forces and multiplying both of them with their respective partial load factor. For sliding, the horizontal forces are seen as unfavourable and will have values higher than one.

For the resisting force, the sum of all vertical forces is calculated, where the vertical force is minimized.

Bearing capacity

Calculating the vertical forces acting on the foundation is the same in the USA and UK, as both use a Meyerhof-type distribution. France does not assume this distribution but just takes the summation of all vertical forces. Germany does this as well, but there are two extra vertical forces because of their earth pressure assumptions.

The bearing resistance design value, q_n, for a soil with no cohesion, depth, ground, or base inclination, is calculated the same way in each country, equation 1.

$$R_{n,k} = (L - 2e) * (\Upsilon_f * (L - 2e) * N_{b0} * i_b \qquad \text{Eq.1}$$

However, the calculation of N_{b0} is quite different as the USA and presumably the UK (no instructions are given) calculated it using Vesic his equation (a=2). While France and Germany do not (a=1), equations 2 and 3. This differs from Eurocode 7 [6], which states in Annex D that a=2.

$$N_{d0} = e^{\pi * \tan \phi'_f} * \tan^2(45 + \frac{\phi'_f}{2}) \qquad \text{Eq. 2}$$

$$N_{b0} = a(N_{d0} - 1) * \tan \phi'_f \qquad \text{Eq. 3}$$

Overturning

Overturning is only checked in the USA and Germany. For both this translates to calculating the eccentricity of the bearing pressure resultant and analysing the result.

Global failure

Global failure occurs when the wall slides on failure planes passing behind and under the reinforced zone. Analyses can be performed using a classical slope stability analysis method with standard slope stability computer programs.

3 Internal Stability

There are three main calculation methods that are used in the four guidelines. The USA uses the Simplified method [7], which uses parts of the Structure stiffness method [8]. The UK and France both use the Tieback Wedge method [9]. Both of these methods calculate the maximum tensile force (T_{max}) per reinforcement layer. The critical slip surface in a simple reinforced soil wall, i.e. a wall with a vertical face and horizontal backfill, is assumed to coincide with the locus of the maximum tensile force in each layer, Figure 3. This critical slip surface is assumed to be a Rankine failure surface for extensible reinforcement, Figure 4. The German guideline considers all possible slip planes and the most unfavourable mechanism is investigated by doing a wedge stability check.

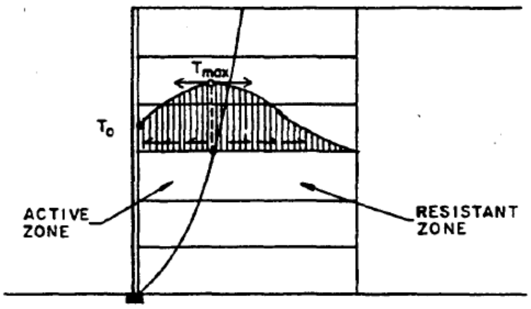

Figure 3: Maximum tensile forces line, general [8]

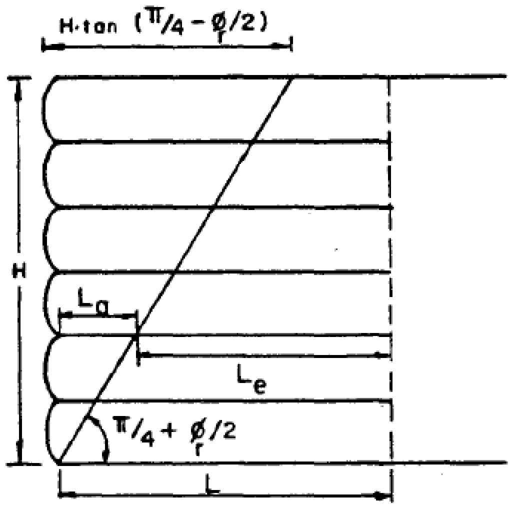

Figure 4: Maximum tensile forces line – Extensible reinforcement [8]

Tieback Wedge Method

In the Tieback Wedge Method, the wall is assumed for internal design to be flexible. Therefore, the lateral soil stress behind the wall reinforcement have no influence on the vertical stresses within the reinforced wall zone, and the vertical stresses acting on a reinforcement layer are simply the weight of the soil plus the traffic surcharge (for a simple wall). It assumes that enough deformation occurs to allow an active state of stress to develop. Hence the lateral earth pressure coefficient K_a is used. T_{max} is determined using equation 4.

$$T_{max} = S_v * K_a * \sigma_v \qquad \text{Eq 4.}$$

With S_v the vertical spacing between the reinforcement layers and σ_v the vertical pressure acting on the reinforcement layer.

However, the UK and French guideline does not simply take the summation of the vertical forces for the vertical pressure, but uses a Meyerhof-type distribution. This is different from the original method.

Simplified Method

This method is similar to the Tieback Wedge Method, but the lateral earth pressure coefficient is determined as a function of depth below the wall top, reinforcement type, and global wall stiffness, rather than using K_a directly. The equation for T_{max} becomes:

$$T_{max} = S_v * K_r * \sigma_v \qquad \text{Eq 5.}$$

The K_r/K_a ratio is taken from a graph, see Figure 5.

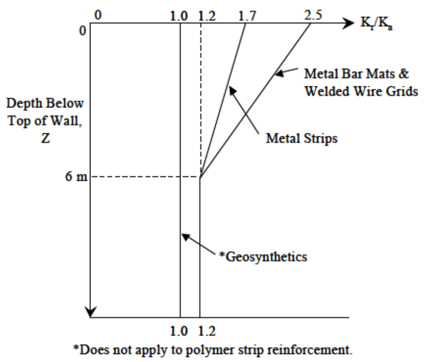

Figure 5: Determination of K_r/K_a [7]

As seen on Figure 5, for geosynthetics the ratio is 1, which means that the Simplified Method and the Tieback Wedge Method are identical for geosynthetics.

Rupture

Rupture is checked by making sure that T_{max} does not get bigger than T_r, which is calculated by applying a resistance partial facture to T_{al}, which can be found in the technical sheets of the reinforcement and is provided by the manufacturer. There are three partial factors specified by the manufacturer (RF_{ID}, RF_{CR} and RF_D) which also need to be applied to T_{al}.

Pull-out

Pull-out of the reinforcement is checked by equation 6:

$$L_e \geq \frac{T_{max}}{\phi * C * F^* \propto \gamma z' R_C} \qquad \text{Eq. 6}$$

With ϕ, the resistance factor for soil reinforcement pull-out, C is 2 (for strip, grid and sheet type reinforcement, and π for circular bar reinforcements), F* is the pull-out resistance factor calculated by:

$$F^* = {}^2\!/_3 \tan\phi \qquad \text{Eq. 7}$$

α is the scale effect correction factor, $\gamma_r z'$ is the overburden pressure including distributed surcharges (not including traffic surcharges), R_c is the reinforcement coverage ratio and L_e is the length of the embedment in the resisting zone.

Wedge stability check

The wedge stability check is used in Germany and does not calculate T_{max} for each layer. It considers all possible slip planes and the most unfavourable failure mechanism is investigated, so it's not a local stability check at each layer but rather the stability of the entire wedge.

Various slip planes need to be investigated, so the calculations need to be done for each one. All (acting) mobilising forces are compared to the total (resisting) restraining force of the reinforcement. The plane with the highest mobilising forces needs to be investigated.

The resistance for rupture is calculated the same way is in the USA, UK and France. The resistance for pull-out is given by equation 8:

$$R_{Ai,d} = 2 * \sigma_{v,di} * L_{e,i} * (\frac{f_{sg,k}}{\Upsilon_B}) \qquad \text{Eq.8}$$

With γ_B the resistance factor for pull-out and $f_{sg,k}$ given by equation 9:

$$f_{sg,k} = 0{,}8 * \tan \phi_{r,k} \qquad \text{Eq.9}$$

With $\phi_{r,k}$ the angle of internal friction of the reinforced soil.

Failure by rupture and pull-out of the reinforcement elements shall be examined on the resistance side. Safety assumed if the following limit state condition is met, equation 10:

$$\sum F_{d(\vartheta)} \leq \min(\sum R_{Bi,d}; \sum R_{Ai,d}) \qquad \text{Eq.10}$$

The governing value for each layer is the smaller one.

4 Analysis of the partial factors

In Table 1 an overview is given of all the different partial factors used in the calculations. These will give small differences in the performance ratios. Most guidelines state which load factor to use (unfavourable or favourable), depending on which calculations need to be done. The UK guideline summarizes this in different load combinations A,B and C. Combination A is the most unfavourable one with all the unfavourable load factors, Combination B states that the vertical load is a favourable load and that the traffic surcharge on the reinforced fill is not included, and combination C states that all loads are favourable and that traffic surcharge is not included, both on the reinforced fill and the retained backfill, which is the combination used for serviceability limit state.

The resistance factors in the US were inverted so they can easily be compared to the others. The partial material factors are only applied for calculating the internal stability.

Table 1: Comparison of different load factors

Unfavourable load Factors	**US**	**UK**	**FR**	**DE**
Vertical load	1,35	1,5	1,35	1,35
Horizontal load	1,5	1,5	1,35	1,35
Surcharge	1,75	1,5	1,5	1,5
Favourable load factors	**US**	**UK**	**FR**	**DE**
Vertical load	1,0	1,0	1,0	1,0
Horizontal load	1,0	1,0	1,0	1,0
Resistance factors	**US**	**UK**	**FR**	**DE**
Sliding				
Soil-Reinforcement	1,0	1,3	1,1	1,1
Soil-Soil	1,0	1,2	1,1	1,1
Bearing resistance	1,5	1,5	1,4	1,4
Materials				
Tan φ’	1,0	1,0	1,0	1,25
Tensile resistance	1,1	N/A	1,25	1,4
Pullout resistance	1,1	1,3	1,35	1,4
Economic ramifications of failure	N/A	1,0-1,1	N/A	N/A

The partial load factors only have small differences, except for the surcharge load factor in the US, which is 1,75. For the resistance factors, the biggest difference is in the US resistance factors, which are smaller than the other three countries, except for the bearing resistance factor. The resistance factor for sliding in the UK is also substantially bigger than the other three countries . As for the partial material factors, they are only mentioned in the UK and German guideline, however, they only have an impact in the German guideline, as the value in the UK is 1. The partial factor for economic ramifications of failure is only applied in the UK, at both rupture and pull-out calculations. There is however no resistance factor for rupture in the UK.

France follows Eurocode 7 [6], Design Approach 2. Germany does the same but differs in the partial material factors.

5 Analysis of the performance ratio's

A simple reinforced soil wall, with a design height of 8,6m and a reinforcement length of 6m, see Figure 6, was designed using the four different guidelines.

Overdesign ratios were calculated for sliding, bearing capacity, rupture of the reinforcement and pull-out of the reinforcement. This was done for each of the four guidelines, to give a clear overview of the conservativeness of each guideline.

Sliding

The ODR for sliding are calculated by dividing the factored resisting force by the acting sliding force. Only sliding on the reinforcement is compared, as this is the worst case scenario for each country.

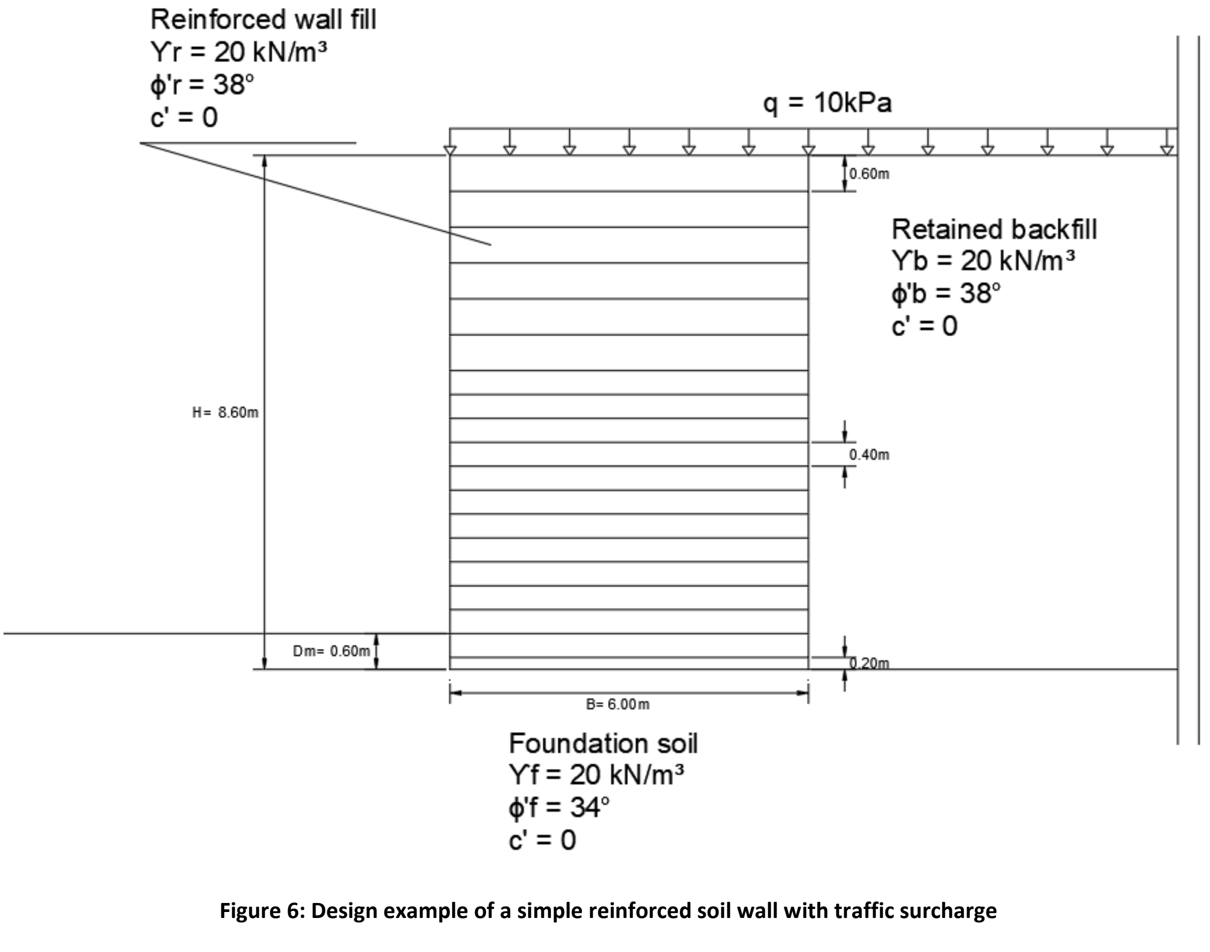

Figure 6: Design example of a simple reinforced soil wall with traffic surcharge

As seen on Figure 7, the ratio's for sliding are in the same range of 1,70 to 1,85, except for the UK, which is at 1,40. All four guidelines use the same way of calculating the resisting and acting forces, so the difference is mainly because the partial resistance factor against sliding on reinforcement, which is 1,3 in the UK in comparison to the 1,1 in Germany and France, and even the 1 in the USA. The small differences between the USA, France and Germany are in the partial load factors.

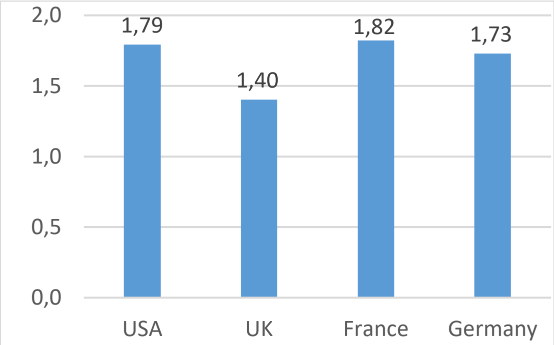

Figure 7: ODR for sliding

Sliding

The ODR for the bearing on the foundation are calculated by dividing the factored bearing resistance by the vertical pressure acting on the foundation.

As seen on Figure 8, the ratio's for bearing in the USA and the UK are rather high, between 4 and 4,5 and between 2,45 and 2,50 for the France and Germany. If we take a closer look at the equations used for bearing on the foundation, the biggest difference is in the calculating of the factored bearing resistance.

N_{b0} is calculated to be 19,18 in France and Germany, while in the USA and UK it is calculated using Vesic's equation, which states that for an internal friction angle of 34° it is 41,1. This is a bit more than twice the value of France and Germany, which explains why the performance ratio of the USA and the UK is almost double that of France and Germany.

The reason why the UK ratio is 0,43 greater than the USA one is because of the extra term $Y_f D_m$ which is added to the bearing resistance calculation.

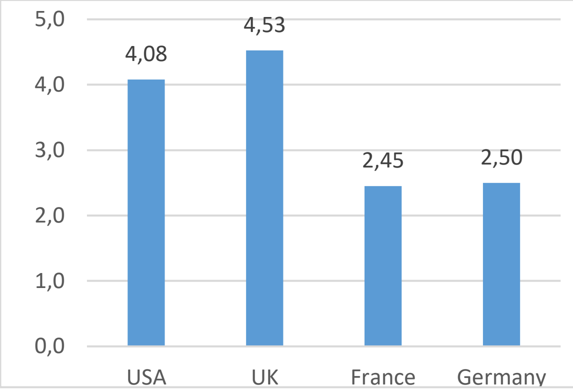

Figure 8: ODR for bearing capacity

Rupture of the reinforcement

The ODR for rupture are calculated by dividing the allowable tension force by the T_{max} of the bottom layer, which is the biggest value. For Germany the ratio is slightly different as the way of calculating rupture failure does not use T_{max} but rather combines both rupture and pull-out in one calculation. So the ratio of Germany is the resisting forces divided by the acting forces and is a general ratio for internal stability.

As seen on Figure 9, the performance ratios are between 2,10 and 1,50. The USA's performance ratio's is this great because of the way T_{max} is calculated. The value of T_{max} in the bottom layer is 22,87 kN/m for the USA, 30,72 kN/m for the UK and 27,88 kN/m for France. The USA one is lower because it does not assume a Meyerhof-type distribution for the vertical pressure on the reinforcement layer, in comparison to the UK and France. The German ratio is also higher but uses a completely different calculation, so the exact reason in comparison to the others cannot be given. The small differences between the UK and France are because of different partial load and resistance factors.

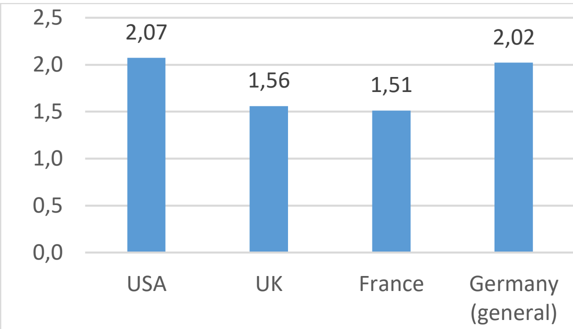

Figure 9: ODR for reinforcement rupture

Reinforcement pull-out

The ODR for pull-out is calculated by dividing the available pull-out length by the required pull-out length.

They are only for the top layer as the ratio is the smallest there. The German ratio is again dividing the resisting forces by the acting forces and is a general performance ratio for internal stability.

The results are given on The differences between the USA, UK and France are due to the differences in partial factors. The German ratio uses a completely different calculation, so the exact reason in comparison to the other cannot be given.

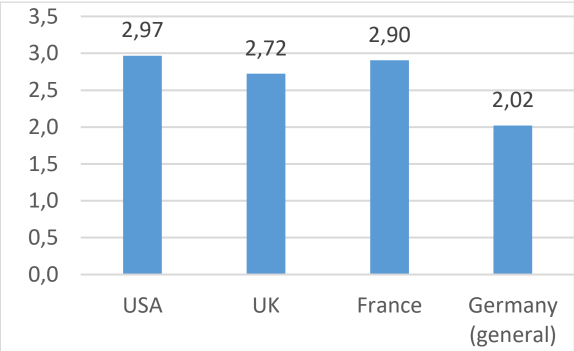

Figure 10: ODR for reinforcement pull-out

5 Analysis of calculations

The four different guidelines all do different calculations and checks to verify both the external and internal stability. Not all calculations were done while designing the wall, only the ones that were explained and where equations were given. The other calculations are mentioned in the guidelines but are not elaborated. In Table 2, an overview is given of all the calculations and checks used in the four different guidelines.

Only the USA and the German guidelines check for overturning, by limiting the eccentricity of the bearing pressure resultant. The UK guideline mentions tilt in the same calculation as bearing but does not actually limit the eccentricity.

Table 2: Calculations and checks used in the different guidelines

	US	**UK**	**France**	**Germany**
Bearing on foundation	X	X	X	X
Overturning (eccentricity)	X	-	-	X
Sliding	X	X	X	X
Settlement	X	X	-	X
Rupture	X	X	X	X
Pull-out	X	X	X	X
Wedge stability		X		X
Connection strength	X	X	X	X
Lateral movements	X	X	X	X
Vertical movement	X	X	-	X
Global stability	X	X	X	X
Compound stability	X	X	X	X
Drainage	X	X	-	-

6 Conclusions

For the internal stability, the US, the UK and France all use calculation methods to calculate T_{max} at each reinforcement layer. The German guideline however only does a wedge stability check on the most critical slip plane. Performing a wedge stability check is only mentioned in the UK guideline but not in the US or French guidelines. Which means that the ratio for both rupture and pull-out for Germany cannot be directly compared to those of the other three countries.

All four guidelines have at least provided equations for calculations in the Ultimate Limit state, but have not done the same for the calculations in the Serviceability Limit State. The calculations are mentioned, and the partial factors are given but they do not go in depth.

Another conclusion is that the partial factors only have a small influence in the differences between the guidelines, the biggest differences come from the different calculation methods that are used.

The main conclusion is that the US guideline is the least conservative guideline for calculating both external and internal stability in the Ultimate Limit State. It cannot be stated however, that the Simplified method is the least conservative compared to the Tieback Wedge method, as a Meyerhof-type distribution is assumed for the vertical pressure on the reinforcement layers in the UK and France, while this is not stated in the original method. If this distribution would not be used, the only differences would be because of the partial factors, at least for the design of this specific wall. This is because the main difference between the Simplified Method and the Tieback wedge method is the use of a K_r/K_a ratio in the Simplified Method, and just K_a in the Tieback wedge method, however for geosynthetics the K_r/K_a ratio is 1, which means the equations become identical.

7 References

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