The design guideline basal reinforced piled embankments; The Dutch CUR226:2016 and the German EBGEO:2010; A comparison of design models and safety approaches

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ABSTRACT: The Dutch Design for geosynthetic-reinforced pile-supported embankments had a major revise before publishing its second version in 2016 (van Eekelen and Brugman, 2016, hereafter called CUR226). This paper compares this new design guideline and the German design guideline EBGEO 2010. The following is compared: (1) the design models that calculate the tensile force in the geosynthetic reinforcement (GR), without using partial factors, and (2) the safety approaches, while using the same GR design model. CUR226 uses the Concentric Arches model for the design the geosynthetic reinforcement (GR, van Eekelen et al., 2012a, 2012b, 2013, 2015), which is a modification and extension of EBGEO's model (Zaeske, 2001). It is concluded that the EBGEO model calculates on average 2.5 times the GR strain measured in many projects, while the CUR226 model calculates on average 1.1 times that measured strain: a nearly perfect fit. CUR226 uses partial safety factors for load and material parameters that were determined using a probabilistic study (van Duijnen et al., 2015). EBGEO uses partial factors on load effect and GR resistance. It is concluded that the most strict reliability class of EBGEO, Lastfall 1, equals or exceeds the least strict reliability class of CUR226 (RC1, applied for roads) for most geometries that are applied frequently, as long as the subgrade reaction is less than 100 kN/m^3, for the considered cases. However, Lastfall 1 is in most cases less safe than the most strict reliability class of CUR226: RC3, which is applied for railways.

Keywords: safety approach, geosynthetic reinforcement, pile-supported embankment, partial factors

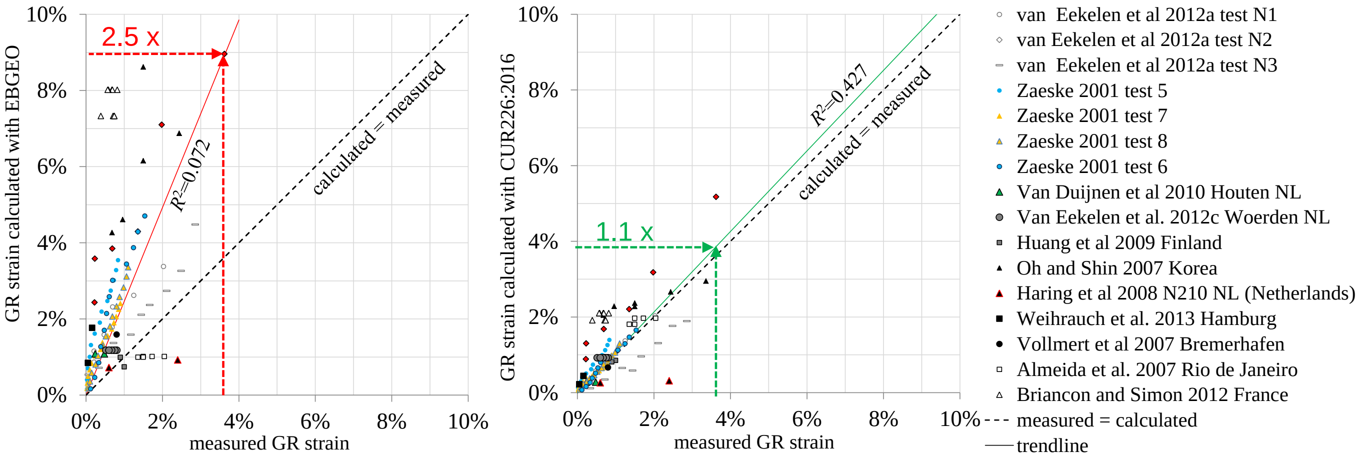
1 INTRODUCTION

The Dutch Design Guideline CUR226 (van Eekelen and Brugman, 2016, see also van Eekelen, 2016, called 'CUR226' in this paper) for geosynthetic-reinforced pile-supported embankments had a major revise before publishing its second version in 2016. This paper analyses some main differences between this new guideline and the German design guideline EBGEO (version 2010, called 'EBGEO' in this paper). First, Section 2 briefly compares the models that calculate the GR tensile forces. After that, Section 3 compares the safety approaches. This paper focuses on geosynthetic reinforcement (GR) design only.

2 CALCULATING THE GR TENSILE FORCE IN EBGEO AND CUR226

For the GR design, the GR strain needs to be calculated, using the GR stiffness as input value. Multiplying this GR strain by the GR stiffness gives the GR tensile force. During designing, it should be checked that the design value of the GR tensile force $T_{s;d}$ is smaller than the design value of the long-term GR tensile strength $T_{r;d}$.

EBGEO uses the calculation model of Zaeske (2001) for GR design. Figure 1*a* shows that Zaeske's model gives on average 2.5 times the strain measured in nine field cases and seven laboratory experiments (Van Eekelen et al., 2015). CUR226 uses the Concentric Arches (CA) model. This model was developed on the basis of a series of lab tests and validated with more than 100 measurements in 11 projects, and with numerical calculations (van Eekelen, 2015, van Eekelen et al., 2012a, 2012b, 2013, 2015, van der Peet and van Eekelen, 2014). Figure 1*b* shows that the GR strain calculated with the CA model is on average 1.1 times the measured GR strain. Furthermore, the dots in Figure 1*b* coincide more closely with the trend line than the dots in Figure 1*a*. It is concluded that the CA model gives an almost perfect match with the measured GR strain. This is the reason that the CA model has been adopted in CUR226 and will be mentioned in the upcoming revision of EBGEO to be usable for calculating serviceability limit state. Beyond that it is interesting to study how the CA model combines with the German safety approach. Section 3 gives a first impression of this combination.



a. calculations with EBGEO *b. calculations with CUR226:2016*

Figure 1. Comparison of calculations and measurements in field projects and series of experiments. Calculations were done without partial safety factors. Figure modified after van Eekelen, 2016 and van Eekelen et al., 2015. The references of the measurements are listed fully in van Eekelen et al., 2015, and could not be given in this paper due to space limitations.

3 SAFETY APPROACHES EBGEO AND CUR226

Sections 3.1 to 3.3 and Figure 2 introduce the safety approaches of EBGEO and CUR226. Section 3.4 presents calculations on a standard geometry with the CA model, combined with the safety approaches of EBGEO and CUR226. Section 3.5 analyses results of calculations in which parameters have been varied.

3.1 *Design values of GR tensile force and strain in EBGEO*

Figure 2 gives an overview of the approaches of EBGEO and CUR226. EBGEO calculates with characteristic values for material properties and load first. This results in characteristic values for GR tensile strain and therefore tensile force. Next, the design values of the GR tensile force are calculated using the partial safety factors given in Table 1.

Table 1. Partial safety factors of EBGEO, compilation from Table 2 and Table 3 of the German DIN 1054:2005, which was still applicable when EBGEO (2010) was published, and for η_M from EBGEO.

Partial safety factor		SLS		Lastfall* 1	Lastfall* 2	Lastfall* 3
GR tensile force due to permanent load	γ_G	1.00		1.35	1.20	1.00
GR tensile force due to traffic load	γ_Q	1.00		1.50	1.30	1.00
GR strength	γ_M	1.00		1.40	1.30	1.20
GR strength	η_M	1.00		1.10	1.10	1.10

* Lastfall 1 – 3: German reliability class (literally: load case). Lastfall 1 is applicable for normal conditions during the lifetime of the structure, therefore: for the ULS of the final state. Lastfall 2 is applicable for conditions during construction or maintenance, and Lastfall 3 is applied for singular or probably never occurring conditions during the lifetime of the structure. In the calculation example of EBGEO this reliability class has been applied for the special case: no subgrade.

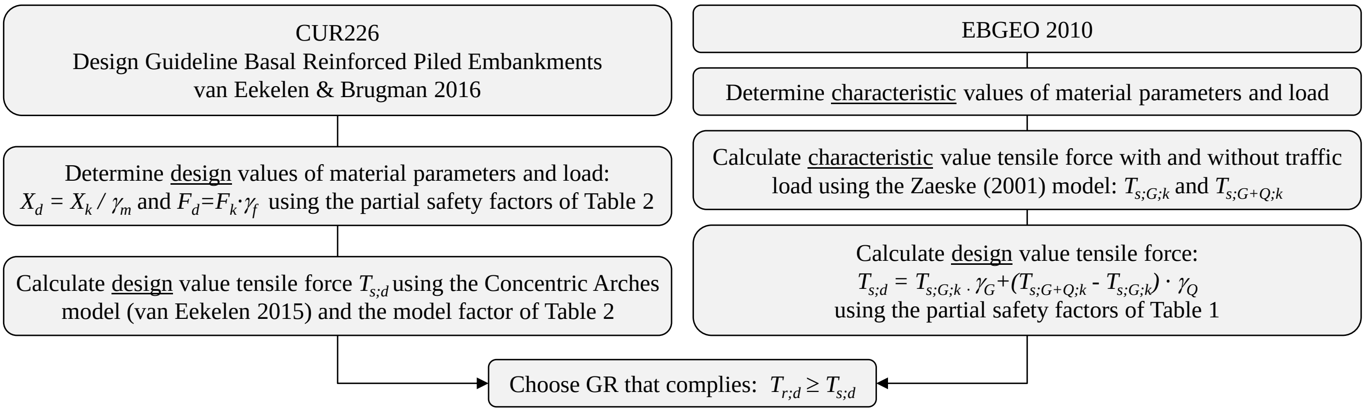


Figure 2. Safety approach for GR design in CUR226:2016 and EBGEO 2010. T = GR tensile force in kN/m, γ = partial safety factor. The following subscripts are used: d = design value, k = characteristic value, G = due to the permanent load, $G+Q$ = due to the permanent + variable traffic load, r = resistance (strength), s = force / load.

3.2 *Design values of GR tensile force and strain in CUR226*

CUR226 calculates with design values for material properties and load. These design values are calculated using the partial safety factors given in Table 2. This set of partial safety factors was determined using a probabilistic study[1] (van Duijnen et al., 2015). Next, the GR strain and GR tensile force are calculated using the Concentric Arches (CA) model and then the result should be multiplied with the model factor γ_M of Table 2 to get the design values of the GR strain and tensile force.

Table 2 Model factor and partial safety factors used for the design of the GR design in CUR226.

		SLS		Reliability class ULS		
Factors***		$\beta^* \geq 2.8$		RC1** $\beta^* \geq 3.5$	RC2** $\beta^* \geq 4.0$	RC3** $\beta^* \geq 4.6$
Model factor	$\gamma_{M;CA}$	1.40		1.40	1.40	1.40
Traffic load p	$\gamma_{f;p}$	1.00		1.05	1.10	1.20
Tangent of internal friction, tan φ'	$\gamma_{m;\varphi}$	1.00		1.05	1.10	1.15
Unit weight fill, γ	$\gamma_{m;\gamma}$	1.00		0.95	0.90	0.85
Subgrade reaction of subsoil, k_s	$\gamma_{m;k}$	1.00		1.30	1.30	1.30
Axial GR stiffness, J	$\gamma_{m;EA}$	1.00		1.00	1.00	1.00
GR Strength, T_r	$\gamma_{m;T}$	1.00		1.30	1.35	1.45

* β is the reliability index required by NEN-EN 1990.
** RC = Eurocode Reliability Classes adopted in CUR226. In the Netherlands, RC1 is in applicable for highways and roads, railways normally demand RC3.
*** γ_M is the model factor of the CA model, γ_f is a load factor, $F_d = \gamma_f \cdot F_k$, γ_m is a material factor, $X_d = X_k / \gamma_m$, a unit weight increase is not beneficial, hence the value of $\gamma_{m;\gamma}$ is less than 1.0.

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[1] van Duijnen et al. (2015) reported the safety analysis used to determine the model factor and the associated load- and material factors. They followed the suggestions made in NEN-EN 1990 (2011, Eurocode 0). They conducted a statistical assessment of the differences between the measured and calculated GR strains and then carried out Monte Carlo (MC) simulations for the SLS situation, for several reference cases, in order to obtain the model factor of 1.4. Multiplying this model factor by the GR strain calculated with characteristic values gives a value that is higher than the real GR strain in 95% of the cases. In other words, if the model factor is used, reality is worse than the calculation in 5% of the cases.

Subsequently, van Duijnen et al. (2015) determined three sets of partial material and load factors associated with the model factor for an approach with partial factors for load, material and resistances. They showed that using this sets of factors satisfy the reliability indices β required by NEN-EN 1990 (2011, Eurocode 0). The resulting model and partial factors were adopted in CUR226 and are shown in Table 2. An advantage of this approach is that the influence of uncertainty in input parameters can be and has been taken into account. This is different to the procedure of EBGEO, where partial factors on load effect and resistances are applied on the characteristic results of strain and force. It would be best to carry out a full probabilistic study for the German safety approach too. This goes beyond the possibilities of this study.

3.3 *Design values of resistances in the Dutch and German design guidelines*

Table 3 shows how EBGBEO and CUR226 determine the design value of the GR tensile strength. A_1 to A_5 are reduction factors that should be determined for the specific reinforcement material in accordance with the applicable standards and guidelines. These reduction factors are usually provided by the GR's supplier and are the same for EBGEO and CUR226. The comparability is not true for the partial safety factors, which is defined as γ_M / η_M within EBGEO, with values 1.27, 1.18 and 1.09 for Lastfall 1, 2 and 3 respectively, and $\gamma_{m;T}$ of CUR226, with values 1.30, 1.40 and 1.45 for of RC1, RC2 and RC3 respectively. This results to the case, that EBGEO's Lastfall 1 (normal conditions) and CUR226's RC1 (roads) are nearly comparable from the GR resistances point of view. The differences in the design strength of these two guidelines are further neglected in this paper.

Table 3*. Calculation design value GR tensile strength in CUR226 and EBGEO

CUR226	EBGEO
$T_{r;lt;d} = \frac{1}{\gamma_{m;T}} \cdot \frac{T_{r;st;k}}{A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_5}$	$T_{r;lt;d} = \frac{\eta_M}{\gamma_M} \cdot \frac{T_{r;st;k}}{A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_5}$

* $T_{r;st;k}$ (kN/m) = the short-term characteristic (subscript *k*) GR tensile strength at the end of production at the factory, with a certainty of 95% to 99%. $T_{r;lt;d}$ (kN/m) = the long-term design value of the GR tensile strength, A_1 to A_5 are reduction factors: A_1 for load duration (creep), A_2 for damage during transport, installation and compaction, A_3 for connections and welded seams, A_4 for influence of the environment, A_5 for dynamic influences. The partial safety factors to reduce the GR strength are $\gamma_{m;T}$ of CUR226 (Table 2) and γ_M and η_M of EBGEO (Table 1).

3.4 *Calculations to compare the safety approaches of EBGEO and CUR226*

This section compares the safety approaches of EBGEO and CUR226. For this purpose, the GR tensile force has been calculated using the same model for each calculation. The CA model of CUR226 was selected for this purpose because Section 2 showed that this model gives the best fit with measurements.

Table 5 gives some results of calculations using the input parameters of the standard case given in Table 4. Table 5 shows the same SLS values for each calculation, as the CA model was applied for each calculation. In this case Lastfall 1 of EBGEO gives approximately the same safety as RC2 of CUR226 (1.38 ≅ 1.39, bold in Table 5 and $T_{s,d;ULSEBGEO;Lastfall\ 1} / T_{s,d;ULSCUR226;RC2} = 0.99 \cong 1.0$, bold in Table 5).

Table 4. Input parameters standard case; modified after the calculation examples in van Eekelen & Brugman 2016

		SLS / $ULS_{EBGEO;\ LF1}$	$ULS_{CUR226;\ RC1}$	
Diameter of circular pile cap (or equivalent diameter of square pile cap)	d	0.85	0.85	m
Embankment height	H	3.50	3.50	m
Centre-to-centre (ctc) pile spacing // and ⊥ to the road axis	$s_x = s_y$	2.25	2.25	m
Unit weight of embankment fill	γ	19.0	20.0*	kN/m^3
Traffic load	p	19.2	20.2*	kPa
Friction angle fill	φ'	45	43.6*	deg
Subgrade reaction (long term, 120 years)	k_s	100	76.9*	kN/m^3
Long-term tensile stiffness of the GR **	J	1692 / 2538	1692 / 2538*	kN/m

* calculated using the partial material and load factors of Table 2

** long term GR stiffness 1629 kN/m parallel to the road axis, 2538 kN/m transverse to the road axis. This was determined using isochronous curves for a geogrid made from PET-filaments with short term GR strength $T_{r;;st;k}$ = 250 kN/m parallel to and 374 kN/m transverse to the road axis; assuming a degree of strain of 3.0% and t = 120 years.

Table 5. Calculated GR tensile forces T_s (kN/m), along the road, using the input parameters of Table 4.

	SLS* without traffic load	SLS* with traffic load	ULS** with traffic load	ULS/SLS with traffic load	Ratio EBGEO/CUR*** Lastfall 1/ RC1 Lastfall 1/ RC2 Lastfall 1/ RC3
EBGEO Lastfall 1	41.13	52.69	72.86	**1.38**	
EBGEO Lastfall 2	41.13	52.69	64.38	1.22	
EBGEO Lastfall 3	41.13	52.69	57.69	1.10	
CUR226 RC3	41.13	52.69	83.25	1.58	72.86/83.25 = 0.88
CUR226 RC2	41.13	52.69	73.50	**1.39**	72.86/73.50 = **0.99**
CUR226 RC1	41.13	52.69	65.20	1.24	72.86/65.20 = 1.12

* Characteristic values (including the model factor $\gamma_{M;CA}$ = 1.4).
** Design values, taking safety approach of Table 1 (EBGEO) and Table 2 (CUR) into consideration
*** See also Figure 4

3.5 *Parameter variation*

Calculations were conducted varying 6 parameters, using the same CA design model: embankment height H (m), centre-to-centre pile spacing s (m), pile cap diameter d (m), fill friction angle φ (deg), surcharge load (traffic) p (kPa) and subgrade reaction k (kN/m^3). Figure 3 to 5 present a selection of the results. The left-hand graphs of Figure 3 show the GR tensile forces in the direction along the road axis and the right-hand graphs across the road axis, in which the spreading force has been included. The forces calculated along the road axis are lower than across, as spreading forces are not relevant along the road axis.

As expected from Table 5, ULS EBGEO Lastfall 1 and ULS CUR226 RC2 show a close fit. For other comparisons, the tensile forces calculated using the EBGEO safety approach show a more clear deviation to the safety concept of CUR226 for the calculations along the road axis. Therefore, in this discussion, the direction along the road axis is considered.

The ratio of the design values of the GR tensile forces, $T_{r;d;EBGEO;Lastfall\ 1}$ / $T_{r;d;CUR226;RC1\ toRC3}$, is given in Figure 4. This value gives an indication of the safety approach of Lastfall 1 of EBGEO in comparison to CUR226. If the design GR tensile force of EBGEO and CUR226 would be the same, the value of Figure 4 should have a value of 1.0. This is nearly the case for Lastfall 1 and CUR226-RC2 of the standard case of Section 3.4. This standard case is indicated with three circles in each graph of Figure 4.

As expected, the trends in Figure 3 are similar for EBGEO and CUR226, resulting in relatively constant values in Figure 4. In many calculations, the safety approach Lastfall 1 of EBGEO gives more or less the same reliability as CUR226-RC2, resulting in values close to 1.0 in Figure 4. Please, note that this Section considers only the safety resulting from the safety approach of EBGEO in comparison to CUR226, and not the differences resulting from the calculation models, which has been considered in Section 2. Keeping that in mind, the following trends are observed in Figure 3 and Figure 4:

- The value of pile spacing s does not have an influence on the safety of EBGEO in comparison to CUR226 for pile spacings that are normally in use: 1.5 m < s < 2.5 m;
- The values of the pile cap diameter d does not have an influence on the safety of EBGEO in comparison to CUR226;
- EBGEO gives a lower safety than CUR226 for 45° < φ < 55°. This might be negligible comparing Lastfall 1 to RC2, but not for the comparison of Lastfall 1 to the highest reliability class RC3. The influence of φ dependents on the height of the embankment and the surcharge load as shown later in Figure 5; for lower friction angles, the EBGEO approach requires higher safety.
- Increasing embankment height gives decreasing safety of EBGEO in comparison to CUR226, although the influence decreases with increasing height;
- Decreasing surcharge load gives decreasing safety of EBGEO in comparison to CUR226;
- Increasing subsoil stiffness (subgrade reaction k) gives decreasing safety of EBGEO in comparison to CUR226. The influence of k is the most significant of all parameters considered.

Within normal geometries ($H \geq 2.25$ m), the safety of EBGEO in comparison to CUR226 depend relevantly on the fill friction angle φ and significantly on the subgrade reaction k. This is understandable as these parameters have a significant influence on the results of Zaeske (2001) and the CA model (van Eekelen, 2015), as shown by van Eekelen et al., 2015. In CUR226, the values of φ and k are reduced by partial factors. In EBGEO, this is not the case. Reducing the subgrade reaction k in CUR226 result in more safety for most of the cases, bringing into account the importance of uncertainty in this important parameter, while the EBGEO safety approach requires more safety at very weak subsoil conditions.

Figure 5 further analyses the influence of k, φ and H and p, and shows values for the required subgrade reaction k, assuming that EBGEO Lastfall 1 needs to equal the safety of RC1 or RC3 of CUR226. Is the subgrade reaction less, than EBGEO exceeds the CUR safety. See Figure 4, bottom right. The influence of the traffic load reduces for increasing embankment height. The influence of the fill friction angle φ and the subsoil stiffness k, are dependent on each other. We conclude that for road applications, Lastfall 1 of EBGEO equals or exceeds the safety level of CUR226 in many cases, but in *all* cases if $k \leq 100$ kN/m^3. This is true for all values of s, d, p, H and φ. For railway purposes, however, Lastfall 1 equals or exceeds RC3 only for no-subsoil situations in combination with limited embankment height (≤ 3.5 m in this case). Thus, the safety concept and approach used by EBGEO can be applied to the CA model, but an extra factor should be applied in EBGEO to reach the safety of RC3 that is applicable for railways in CUR226.

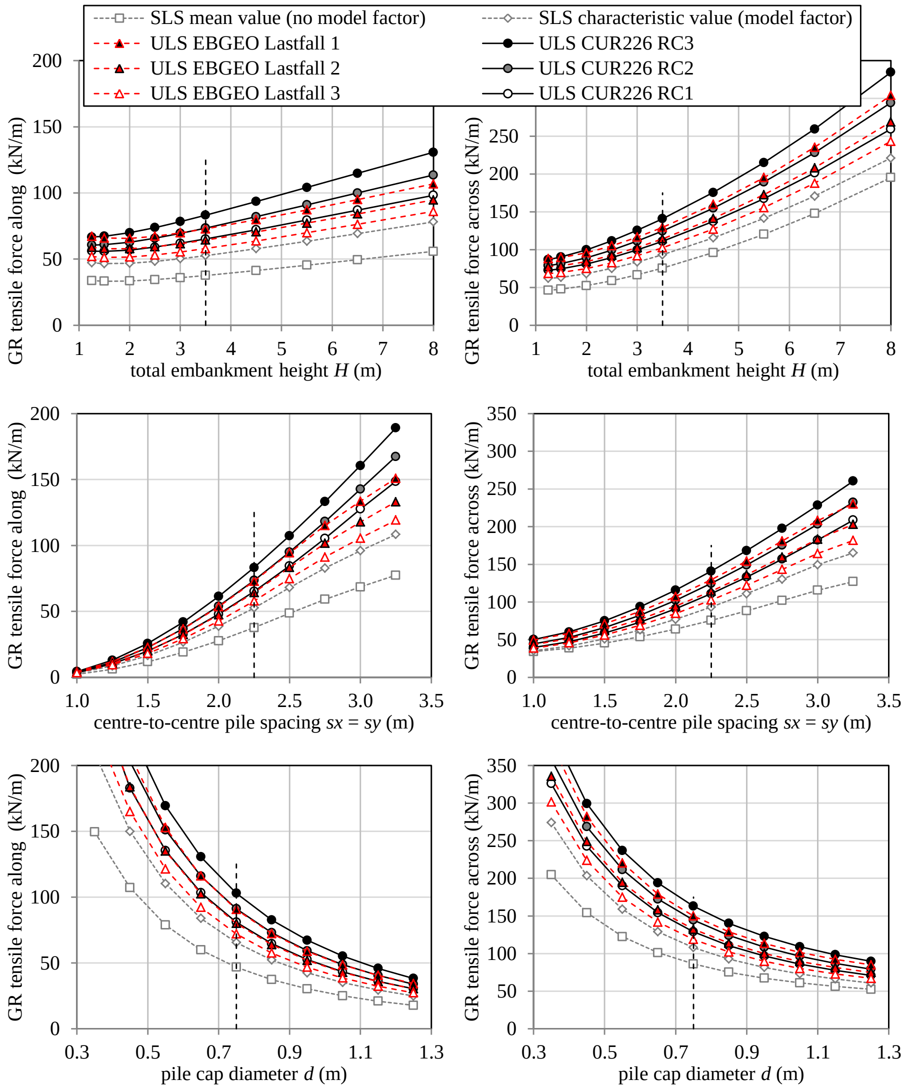

Figure 3. Comparison of safety approaches based on CA model: Calculated GR tensile forces T_s (kN/m) along (left) and across (right) the road axis. All calculations have been carried out with the Concentric Arches model of van Eekelen et al. (2013, 2015) and the input parameters of Table 4 except the varying parameter on the horizontal axis. The standard case of Table 4 and Table 5 is indicated with a vertical dotted line.

4 CONCLUSIONS

This paper compares the GR design concept of two design guidelines: the German EBGEO (2010) and the Dutch CUR226 (van Eekelen and Brugman, 2016). First, the calculation methods to calculate the GR tensile force have been compared with more than 100 measurements. Partial safety factors were not taken into account. It was concluded that EBGEO calculates on average 2.5 times the measured GR strain. CUR226 calculates on average 1.1 times the measured GR strain, which is nearly a perfect fit. Furthermore, the dots resulting from the CUR226-comparison coincide more closely with the trend line than those of EBGEO (Figure 1).

Second, the safety approaches of EBGEO and CUR226 have been compared. For this purpose, the influence of the partial factors of EBGEO and CUR226 has been studied using the same design model for all calculations: the Concentric Arches model of CUR226. EBGEO uses partial safety factors on the load effect and resistances *after* calculating the characteristic forces. In opposite, CUR226 uses partial safety factors for load and material parameters as well as resistances before calculating forces. For CUR226 it was proven that the set of factors satisfy the required reliability indices of the Eurocode (NEN-EN 1990). EBGEO uses Lastfall 1 for all normal conditions during the lifetime of the structure. CUR226 uses reliability class RC1 for road applications and RC3 for railways.

The safety that results from the safety approach of EBGEO in comparison to CUR226 depends on the geometry, load and soil parameters. The influence of the subgrade reaction *k* is the most significant. For road applications, the safety approach of EBGEO equals or exceeds the safety of CUR in many cases. For these road applications, it was found that the safety approach of EBGEO equals or exceeds the safety level of CUR226 in *all* cases for $k \leq 100$ kN/m^3. For railway purposes, however, EBGEO equals or exceeds RC3 only for no-subsoil situations in combination with limited embankment height.

The results of this study give the opportunity to update the design model of EBGEO. Comparing the models as such, a deviation of 2.5 in comparison to the calibrated CA-model opens a perspective to more accurate and economic design. On the other hand, the different safety approaches require a very detailed and careful discussion, as shown by the findings of this study. As example, using the CA-model in combination with the German safety concept (as used by EBGEO and defined by DIN1054:2005, updated DIN1054:2010), a modified partial safety factor is required to be applied in Lastfall 1 to reach the safety of RC3 that is applicable for railways in CUR226.

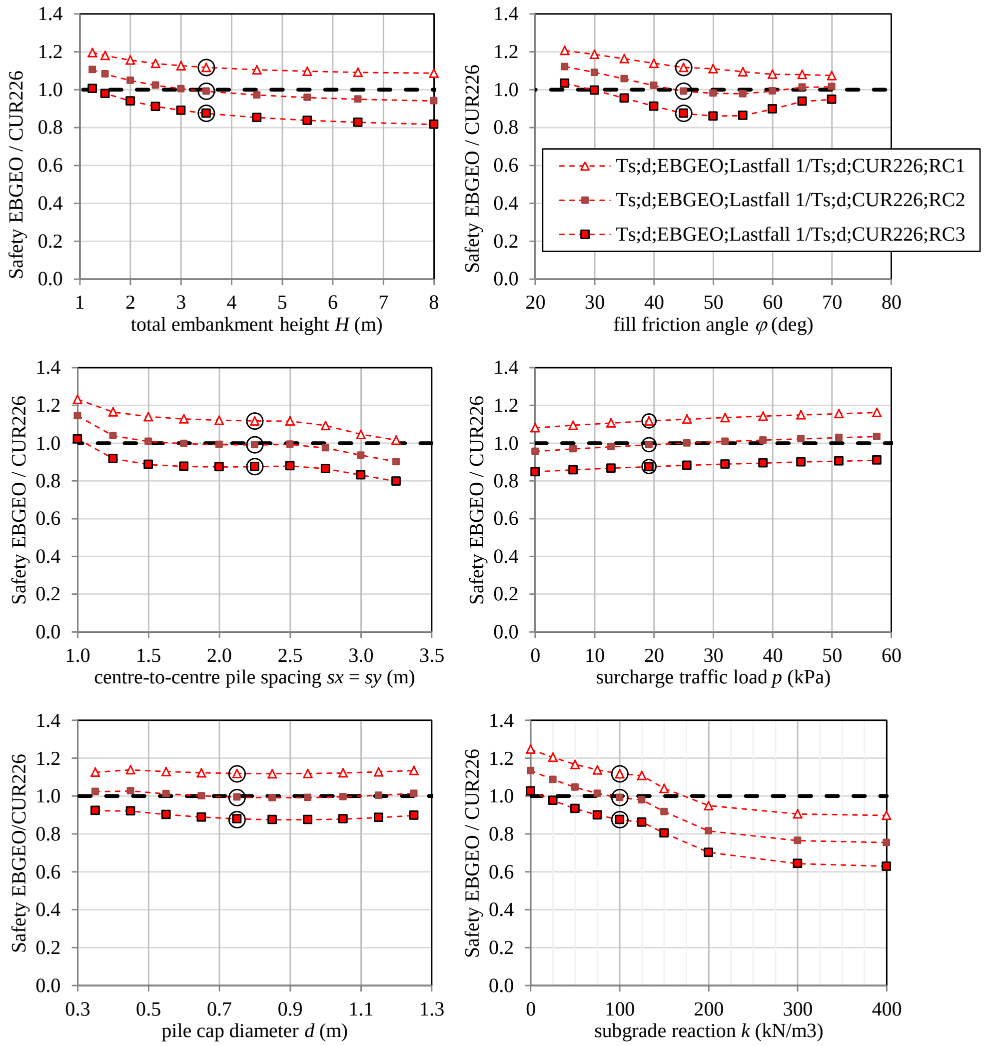

Figure 4. Comparison of safety approaches based on CA model: $T_{r;d;Lastfall\ 1\text{-}EBGEO}$ / $T_{r;d;RC1,2,3\text{-}CUR226}$. Values were calculated as shown in Table 5. The circles O refer to the standard case of Table 4 and Table 5. All results are along the road axis. The left-hand graphs follow directly from the left-hand graphs of Figure 3. The right-hand graphs give results of similar calculations, using the input parameters of Table 4, except the varying parameters along the horizontal axes.

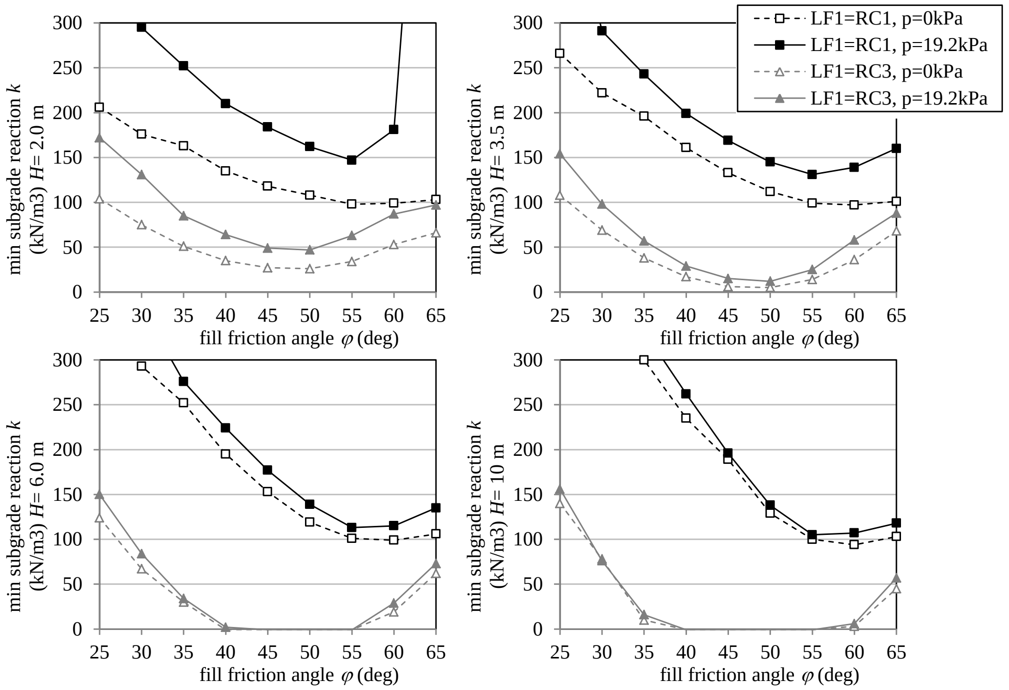

Figure 5. Subgrade reaction range k (kN/m3) calculated based on CA model for which the safety approach Lastfall 1 of EBGEO gives at least the same safety level as RC1, RC2 or RC3 of CUR226:2016. The parameters not mentioned here are given in Table 4. The centre-to-centre pile spacing and pile cap diameter *d* have limited influence and are therefore not considered here. For values of *k* that are equal to or smaller than these values, the safety approach of EBGEO gives a safety that equals or exceeds the safety of the approach of CUR226.

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