Stability of reinforced steep soil slopes to Eurocode 7

Patrick J. Naughton
Institute of Technology Sligo, Ireland

Edoardo Zannoni
Maccaferri Africa, South Africa

ABSTRACT: This study presents an analysis of internal slip circle analysis of reinforced soil slopes with different geometries and varying soil parameters. The stability of the reinforced soil slopes was quantified in an overdesign factor. Angle of friction of the fill was found to have the greatest influence on stability of the slope; stability increased linearly with angle of friction. The pore pressure coefficient also influenced stability, with stability reducing as the pore pressure coefficient increased. Applying a surcharge to the crest of the slope had a more pronounced effect on stability of lower height slopes than higher slopes. The slope face angle and the height of the slope had only a moderate affected on stability. The analysis indicated, that of the currently design codes, SANS 207 (2006) produced the most conservative designs. Eurocode 7 Design Approach 1, Combination 2 and Design Approach 3, were found to be the next most conservative. Replacing SANS 207 (2006) with a Eurocode 7 approach is likely to result in more economic reinforced soil slopes, with the economic benefit dependent on which Design Approach is ultimately adopted. Updating BS 8006-1 (2010) to include Design Approach 1 for the design of reinforced soil slopes could increase the conservatism of UK designs. The analysis presented here indicated that Design Approach 1 is more conservative than BS 8006-1 (2010). This may increase the cost of constructing reinforced soil slopes in the UK.

Keywords: Reinforced slopes, stability, design codes, design, Eurocode 7

1 INTRODUCTION

The development of the Structural Eurocodes was a pan European project, which started in the 1980's, to harmonise the design of building and civil engineering works across the European Union (EU). Since then a suite of ten standards have been developed. From Spring 2010 their use in the design of building and civil engineering works in government financed or owned schemes was compulsory, right across the EU.

Other countries around the world are now investigating adoption of the Eurocodes (Anon, 2006). Singapore, Malaysia and Vietnam have already indicated that they will adopt Eurocodes and South Africa is committed to aligning its national codes with the Eurocodes (Anon, 2016).

This study investigates the influence of different sets of partial factors from existing design codes on the stability of reinforced slopes incorporating geosynthetics. In particular, the influence of partial factors from Eurocode 7 (EN 1997, 2004), the British standard (BS 8006-1, 2010) and the South African standard (SANS 207, 2006) are presented.

2 OVERVIEW OF DESIGN CODES

2.1 *Eurocode 7 (EN 1997-1, 2004)*

The design of geotechnical structures is covered by EN 1997 (2004), commonly referred to as Eurocode 7. Eurocode 7 provides three design approaches (sets of partial factors) that can be used in design. Each country can specify within its National Annex which design approach must be used in that region. Bond

& Harris (2008) summarised the design approach adopted by each member state and reported that 55 % of countries adopted Design Approach 2, 30 % Design Approach 1 and 10 % Design Approach 3. Only one country (Ireland) adopted all three, allowing any of the three design approaches to be used.

Eurocode 7 does not cover the design of structures incorporating geosynthetics. Instead, each National Standards Body could specify the design of these structures in its respective National Annex. Germany rewrote their EBGEO design guidelines (EBGEO, 2011) to make them compliant with Eurocode 7, using Design Approaches 2 and 3, while the French published a number of several new standards, which are fully compliant with Eurocode 7, using Design Approaches 2 and 3. The United Kingdom (UK) National Annex states that BS 8006-1 (2010) should be used for the design of reinforced soil structures (walls, slopes and basal reinforced systems). The UK National Annex also states that the partial factors given in BS 8006-1 (2010) should be used in the analysis and no substitution of partial factors from EN 1997 (2004) should occur. However, BS 8006-1 (2010) states that EN 1997 (2004) (its principles and partial factors) should be used for global slip circle analysis, where the potential slip circular passes wholly outside the reinforced block and for external stability, namely bearing and forward sliding. Interestingly, BS 8006-1 (2010), while a limit state design code, is not Eurocode 7 compliant as it uses significantly different partial factors. The UK has selected Design Approach 1 for use in design. This design approach is further subdivided into Combinations 1 & 2.

2.2 *BS 8006 (1995), SANS 207 (2006) and BS 8006-1 (2010)*

BS 8006 (1995) was the first design code in Europe which covered the design of structures incorporating geosynthetics, including the design of reinforced slopes. BS 8006 (1995) was revised, updated and republished as BS 8006-1 (2010) in late 2010. Both BS 8006 (1995) and BS 8006-1 (2010) adopted limit state approaches to design.

SANS 207 (2006) is the South African code for the design of structures incorporating geosynthetics and was introduced in 2006. For the design of reinforced slopes this code adopted the same partial factors and calculation methods as BS 8006 (1995). Interestingly in both BS 8006 (1995) and SANS 207 (2006) a moment correction factor, χ, was applied to the restoring moment due to the presence of the reinforcement in the method of slices using circular slips and the log spiral method. In both codes the moment correction factor had a value of 1.25 in the method of slices using circular slips and 1.15 in the log-spiral method. The moment correction factor has the effect of reducing the overall factor of safety of the structure, resulting in a more conservative design. In updating BS 8006 in 2010 the moment correction factor was removed from both the method of slices using circular slips and the log-spiral method. However, it is still included in SANS 207 (2006).

2.3 *Partial factors in design codes*

The partial factors used in design can be divided into three principle areas: material factors, action factors and resistance factors. Material factors, excluding those applied to the strength of geosynthetic reinforcement, are applied to the strength and weight of the construction materials. Action factors are applied to both permanent (dead loads in BS 8006 and SANS 207) and variable (live loads in BS 8006 and SANS 207) actions on the structure. In Eurocode 7 actions are considered to be either favourable (increasing stability) or unfavourable (decreasing stability). Resistance factors are applied to the overall resistance the soil mobilises to resist the disturbing actions.

Table 1 summarises the partial factors used in Eurocode 7 and Table 2 the partial factors used in BS 8006 (1995), BS 8006-1 (2010) and SANS 207 (2006) for ultimate limit state (ULS) design.

3 ANALYSIS

The approach adopted in this study was to determine an overdesign factor for a set of reinforced soil slopes with preassigned geometry and reinforcement elements using the different design codes. In this study the term overdesign factor is used as it is more in keeping with the limit state design approach used in Eurocode 7. The overdesign factor is defined as the sum of the force or moments resisting failure divided by the sum of the forces or moment causing failure and is the same as the traditional term factor of safety. No attempt was made to alter the horizontal length or vertical spacing of the reinforcement to optimise the overdesign factor. Analysing the same structure with the different codes would allow a direct comparison of the resultant overdesign factors.

Table 1. Summary of partial factors for the ULS in Eurocode 7.

Parameter		Magnitude of partial factor				
		Design Approach				
		1		2	3	
		Comb. 1	Comb. 2		Strut*	Geo+
Permanent actions	Unfavourable	1.35	1.0	1.35	1.35	1.0
	Favourable	1.0	1.0	1.0	1.0	1.0
Variable actions	Unfavourable	1.5	1.3	1.5	1.5	1.3
	Favourable	1.0	0	1.0	0	0
Shearing resistance (Tanϕ)		1.0	1.25	1.0	1.25	
Effective cohesion		1.0	1.25	1.0	1.25	
Weight density		1.0	1.0	1.0	1.4	
Bearing resistance		1.0	1.0	1.4	1.0	
Sliding resistance		1.0	1.0	1.1	1.0	
Earth resistance, retaining structures		1.0	1.0	1.4	1.0	

* applied to structural actions + applied to geotechnical actions

Table 2. Summary of partial factors for the ultimate limit state in BS 8006 (1995), BS 8006-1 (2010) and SANS 207 (2006)

Parameter	Magnitude of partial factor
Soil unit weight	1.5
External dead loads	1.2
External live loads	1.3
Shearing resistance (Tanϕ)	1.0
Effective cohesion	1.6
Sliding across the surface of the reinforcement	1.3
Pullout resistance of reinforcement	1.3
Sliding along the base of structure where there is soil-to-soil contact	1.2

A series of reinforced soil slopes with different geometries and soil strength parameters were investigated. The generic structure consisted of a slope of height, H, above ground level at the toe of the structure, with a slope face angle, β, and resting on a foundation soil. The reinforcement length, in all layers, was equal to the height H of the slope. The reinforced block was founded 0.5m below ground level at the toe of the structure. A surcharge load of either 0 or 20kPa was applied to the crest of the slope.

The fill in the reinforced block and the retained fill were considered to have the same soil parameters. The unit weight of the fill, γ_b, was held constant at 19 kN/m^3. The angle of friction of the fill, γ_b, and the retained soil was varied between 25^0 and 35^0. The apparent cohesion was zero in all cases. The pore pressure coefficient, r_U, which is defined as the ratio of the pore pressure to the insitu stress in the fill was also varied in both the reinforced block and retained fill.

The reinforced block consisted of coated polyester geogrids with a short-term strength of 50 kN/m, spaced 0.5m vertically in the structure. The partial material factors for the geogrid were taken from the British Board of Agrement (BBA) Certificate 98/R098 Product Sheet 1 and are reproduced in Table 3. The fill was assumed to contain gravel and to have a pH in the range 4 – 9.5. The factor for the ramifications of failure in BS 8006-1 (2010) and SANS 207 (2006) was taken as 1.1 (high). The design life of the slope was 60 years and the design temperature was 20^0C. The bond coefficient, as defined in the BBA Certificate, between the soil and the geogrid was taken as 0.9.

The soil parameters of the foundation soil were held constant in all analysis. This was deemed acceptable as the study focused on the internal stability of the slope. The unit weight of the foundation soil, γ_f, was taken as 19 kN/m^3 and the angle of friction, ϕ_f, as 30^0 with zero apparent cohesion.

Bishop's method of analysis with circular slip surfaces was used in the Maccaferri MacStars W stability software (Maccaferri, 2010), which is Eurocode 7, BS 8006-1 (2010) and SANS 207 (2006) compliant.

Table 4 summaries the range of soil parameters invested in this study, while Table 5 lists the slope geometric parameters investigated.

4 RESULTS

The results of the analysis are discussed, firstly, in terms of how the soil parameters (angle of internal friction and pore pressure coefficient), geometry (slope height and face slope angle) and external surcharge loading influenced the magnitude of the overdesign factor predicted by each code. Secondly, a comparison of the predicted overdesign factors from each code is presented.

Design Approach 1 has two combinations with the lower overdesign factor from these two combinations taken as the critical factor for that design approach. When analysing geotechnical actions Design Approach 1, Combination 2 and Design Approach 3 have identical partial factors and therefore give the same overdesign factor.

Table 3. Partial material factors, 60 year design life and a design temperature of 20^0C, for the coated polyester geogrid taken from BBA Certificate 98/R098 Product Sheet 1

Condition	Magnitude of partial factor
Installation damage, gravel $d_{50} > 22$mm and $d_{90} > 28$mm	1.15
Durability / environmental, $4 \leq pH \leq 9.5$	1.05
Creep	1.37
Ramification of failure, high	1.1

Table 4. Summary of parameters investigated in this study

Soil layer	Angle of internal Friction (^{0})	Unit weight / weight density (kN/m^3)	Pore pressure coefficient, r_U
Reinforced block and retained fill	25, 30, 35	19	0, 0.2
Foundation soil	30	19	0

Table 5. Summary of slope geometries, surcharge and pore pressure coefficients investigated in this study

Parameter	Slope height, H (m)	Angle of face to horizontal, β (^{0})	Length of Reinforcement (m)	Surcharge loading (kPa)	Pore pressure coefficient, r_U
Range of values	3, 5 and 10	45, 55 and 70	3, 5 and 10 Always = H	0 and 20	0 and 0.2

4.1 *Influence of soil parameters, geometry and surcharge loading on overdesign factor*

Figure 2 presents the variation of overdesign factor with angle of friction of the fill deter-mined for a 10m slope with a 45^0 face slope, no surcharge and $r_U = 0$. These results are typical of those determined in this study and, as expected, indicate a linear relationship between overdesign factor and angle of friction for all design codes. Increasing the angle of friction from 25^0 to 35^0 resulted in a 25 – 40% increase in overdesign factor.

The overdesign factor also increased as the slope face angle increased, Figure 3, for a 5m high slope, 30^0 angle of friction, no surcharge and $r_U = 0$. Again these results are typical of those determined in this study. The increase in overdesign factor was not linear with the overdesign factor for the 45^0 and 55^0 slope faces varying by less than 5%, while the slope with a face angle of 70^0 had an overdesign factor 20% higher than that found for the 45^0 slope.

The overdesign factor also increased as the slope face angle increased, Figure 3, for a 5m high slope, 30^0 angle of friction, no surcharge and $r_U = 0$. Again, these results are typical of those determined in this study. The increase in overdesign factor was not linear with the overdesign factor for the 45^0 and 55^0 slope faces varying by less than 5%, while the slope with a face angle of 70^0 had an overdesign factor 20% higher than that found for the 45^0 slope.

The influence of slope height on overdesign factor is shown in Figure 4 for a 70^0 face slope, angle of friction of 300, no surcharge and $r_U = 0$. Interestingly, in this particular case the slope heights of 3m and 10m had similar overdesign factors, while the 5m slope had a slightly higher overdesign factor. The overdesign factor varied up to 10% for the cases examined.

The application of a surcharge to the crest of the slope reduced stability of the structure, with all overdesign factors reducing, Figure 5. The reduction in the overdesign factor was largest (6 – 8% reduction) in the lower height slope, 3m, compared with the higher slopes, 10m (2 – 5% reduction).

After angle of internal friction of the reinforced fill the pore pressure coefficient had the most profound influence on the overdesign factor; increasing r_U from 0 to 0.2 resulted in a 15 - 30% decrease in the overdesign factor. The overdesign factor in SANS 207 went slightly below unity (0.96 & 0.99) indicating an unstable slope for a slope face angle of 45^0.

In all cases analysed SANS 207 (2006) produced the lowest and, therefore, the most critical overdesign factor, Figures 2 – 4, with Design Approach 1, Combination 2 and Design Approach 3 predicting the next lowest set of overdesign factors.

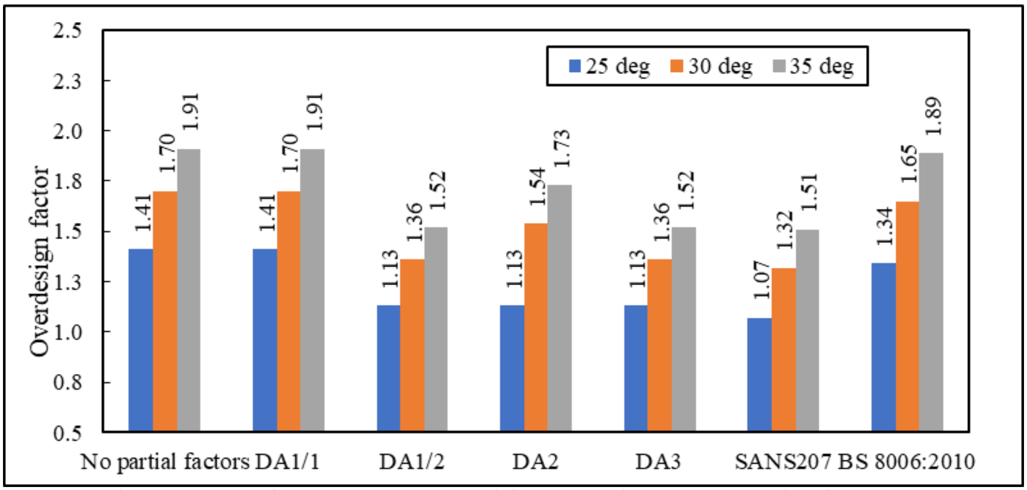

Figure 2: Variation of overdesign factor with angle of friction of the retained fill for a 10m high slope with a slope face angle of 45^0, an angle of internal friction of 300, no surcharge and $r_U = 0$

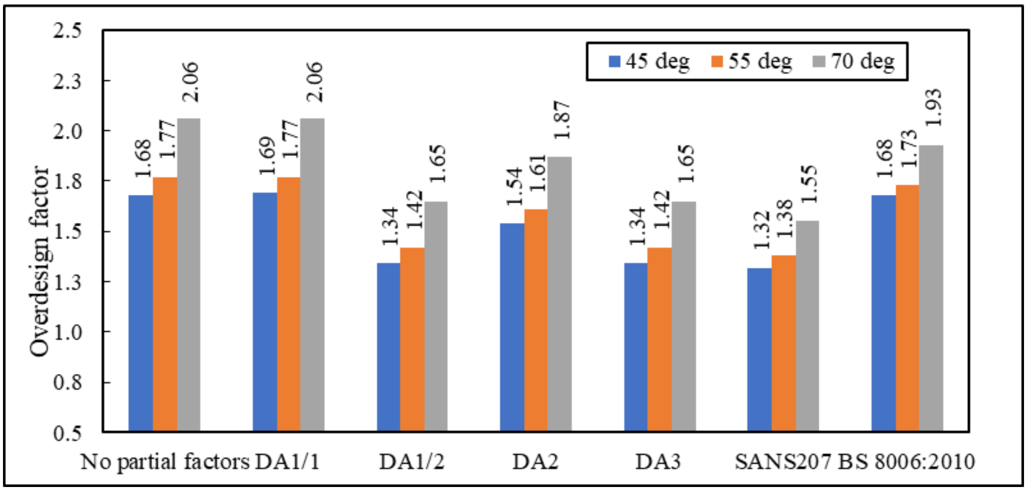

Figure 3: Variation of overdesign factor with slope face angle for 5m high slope with an angle of friction of 30^0, with no surcharge and $r_U = 0$

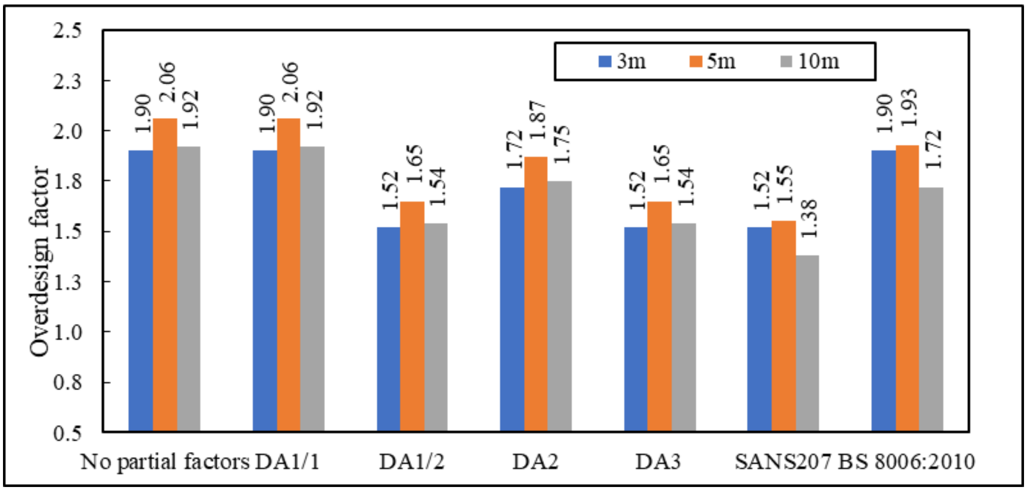

Figure 4: Variation of overdesign factor with slope height for slopes with a slope face angle of 70^0, an angle of friction of 30^0, no surcharge and $r_U = 0$

4.2 *Comparison of overdesign factors from different codes*

Figures 6 – 8 present scatter diagrams of all comparable data of the overdesign factors determined using the three design approaches from Eurocode 7, SANS 207 and BS 8006-1 with no surcharge on the crest of the slope and no pore pressure in the fill, $r_U = 0$. The overdesign factor for Design Approach 2 was found to be consistently 10 – 15% higher than the comparable values for Design Approach 1 and Design Approach 3, Figure 6. Overdesign factors determined using SANS 207 were between 0 – 10 % lower than the critical value for Design Approach 1 and Design Approach 3 and between 10 – 20 % lower than Design Approach 2. Overdesign factors from BS 8006-1 were 10 – 20 % higher than comparable critical values from Design Approach 1, Figure 6.

Scatter diagrams of all comparable data showing the influence of surcharge load on the crest of the slope and pore pressure in the fill are presented in Figures 7 & 8 for 30^0 angle of friction in the fill. BS 8006-1 predicted an overdesign factor that was 15 – 25% higher than that given by Design Approach 1 when both the surcharge load and pore pressure were present. Design Approach 2 was about 10 – 15% higher than Design Approaches 1 and 3 in both case, while SANS 207 was up to 10% lower than both Design Approaches 1 and 3. The only case examined that had overdesign factors less than unity (unstable slope) were found with a 20kPa surcharge on the crest and $r_U = 0.2$ when using SANS 207. The unstable slopes all had 45^0 face slopes.

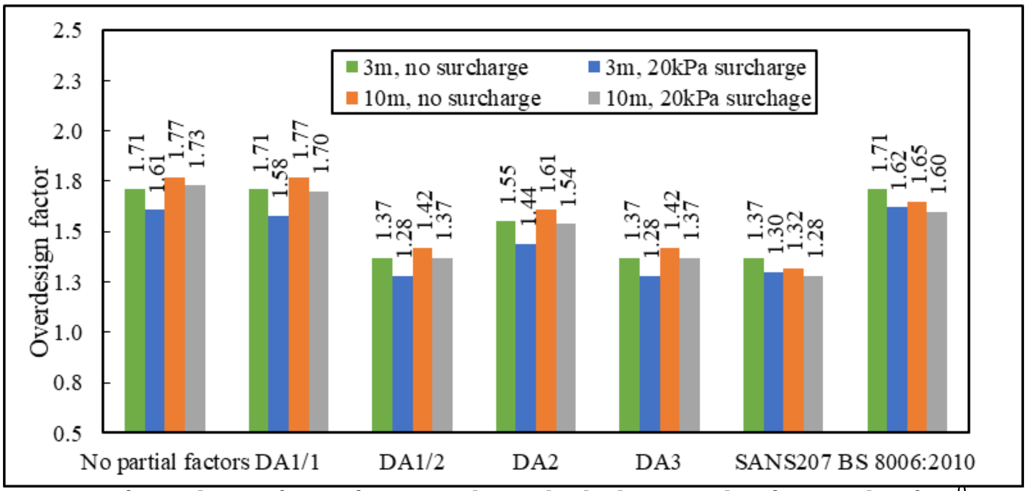

Figure 5: Variation of overdesign factor for 3m and 10m high slopes with a face angle of 55^0, an angle of friction of 30^0, $r_U = 0$ and with no surcharge and a 20kPa surcharge

5 DISCUSSION AND IMPLICATIONS OF RESULTS

The overdesign factor was found to be most dependent on the angle of friction of the reinforced fill and the retained fill. A 50 % increase in the overdesign factor was observed as the angle of friction increased from 25^0 to 35^0 in the reinforced soil and retained fill. The pore pressure coefficient was the next most important parameter, with a 15 – 30% reduction in the overdesign factor as the r_U increased from zero to 0.2. The application of a surcharge load of 20kPa to the crest of the slope had a more pronounced effect in the 3m slope, resulting in a 6 – 8% reduction in the overdesign factor, compared to a 2 – 5% in the 10m slope. The slope face angle and the height of the slope were only moderately affected by changing these parameters over the range of values examined in this study.

SANS 207 (2006) presented the lowest overdesign factor for all cases examined. This design code was therefore the most conservative in terms of slip circle analsyis, which was directly attributable to the moment correction factor, $\chi = 1.25$, used in slip circle analysis. Reducing the moment correction factor to unity would result in SANS 207 (2006) and BS 8006-1 (2010) being identical and producing the same overdesign factor.

Of the three design approaches given in Eurocode 7, Design Approach 1, Combination 2 / Design Approach 3 predicted the lowest overdesign factors and were the next most conservative set of partial factors after SANS 207 (2006). These two approaches apply partial factors to both actions and material parameters. In particular, they apply a factor of 1.25 to the tan of the angle of friction. The overdesign factor was found to be particular sensitive to angle of friction, as indicated in Figures 2 and 3.

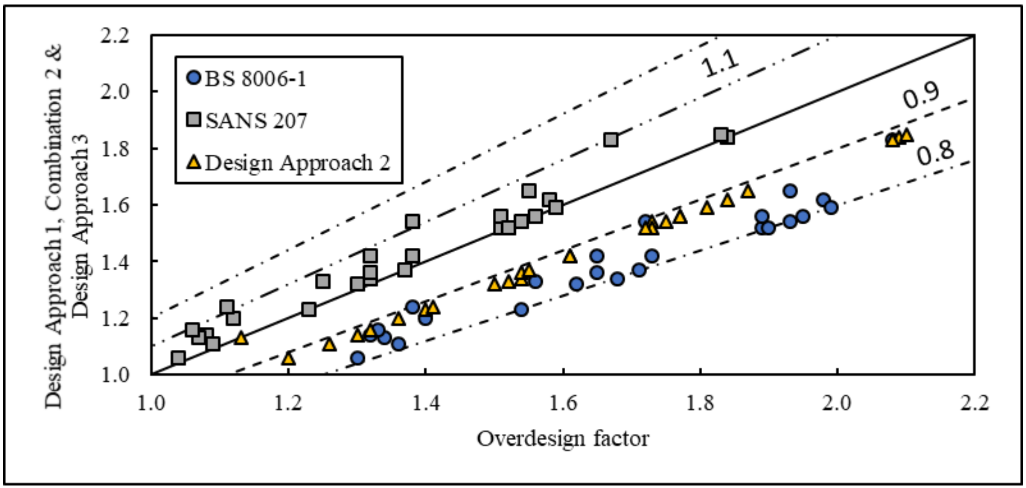

Figure 6: Relationship between overdesign factors from Design Approach 1, Combination 2 / Design Approach 3 and those from BS 8006-1, SANS 207 and Design Approach 2 with no surcharge and $r_U = 0$

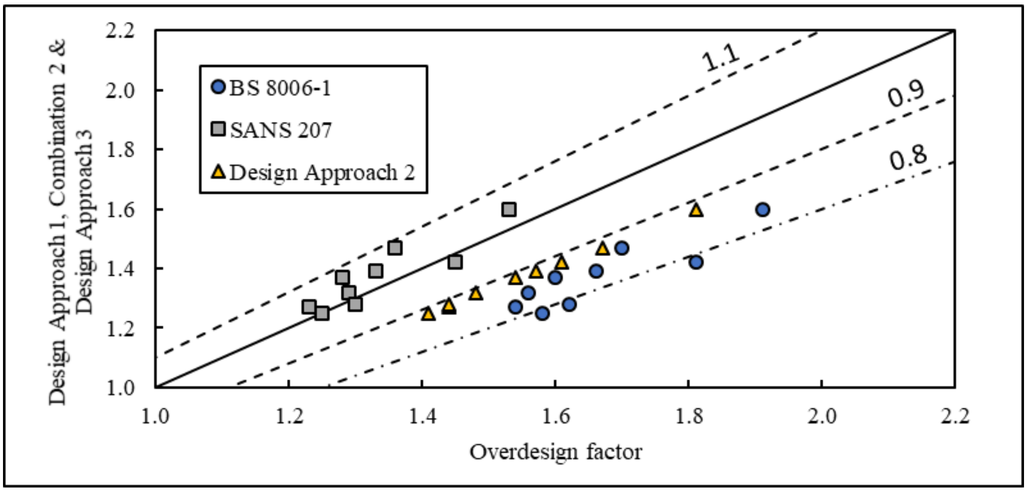

Figure 7: Relationship between overdesign factors from Design Approach 1, Combination 2 / Design Approach 3 and those from BS 8006-1, SANS 207 and Design Approach 2 with a 20kPa surcharge and $r_U = 0$

5.1 *Implications for design*

South Africa has committed to aligning its national standards to the Eurocodes. The design of reinforced slopes will therefore be covered by one of the three design approaches available in Eurocode 7. The removal of the moment correction factor, $\chi = 1.25$, currently applied in slip circle analysis, may, depending on the design approach adopted, increase the overdesign factor for reinforced slopes. Using a less conservative design code will result in a reduction in the area of geogrid required to stability a slope, leading ultimately to more economic reinforced soil structures.

Currently the UK National Annex specifies the use of BS8006-1 (2010) for the design of reinforced soil slopes. In time the UK will move to and adopt a Eurocode 7 compliant design code for internal, as well as external, design of reinforced slopes. In the UK geotechnical structures are design using Design Approach 1, which this study has shown to be the most conservative of the design approaches given in the Eurocode 7. The analsyis presented here indicated that Design Approach 1 was significantly more conservative than BS 8006-1 (2010). Moving to a design methodology based on Design Approach 1 could result in more conservative design of reinforced soil slopes, which may in turn increase the cost of reinforced soil slopes in the UK.

6 CONCLUSIONS

This study presented an analysis of internal slip circle analysis of reinforced soil slopes with different geometries and varying soil parameters. The stability of the reinforced soil slopes was quantified in an overdesign factor, which was defined in the same way as the traditional factor of safety.

Angle of friction was found to have the most significant influence on the magnitude of the overdesign factor, which increased linearly as the angle of friction increased. The pore pressure coefficient also influenced stability, with the overdesign factor reducing as the pore pressure coefficient increased. Applying a surcharge to the crest of the slope had a more pronounced effect on lower height slopes than higher slopes. The slope face angle and the height of the slope had only a moderate effect on the overdesign factor for the range of values examined in this study.

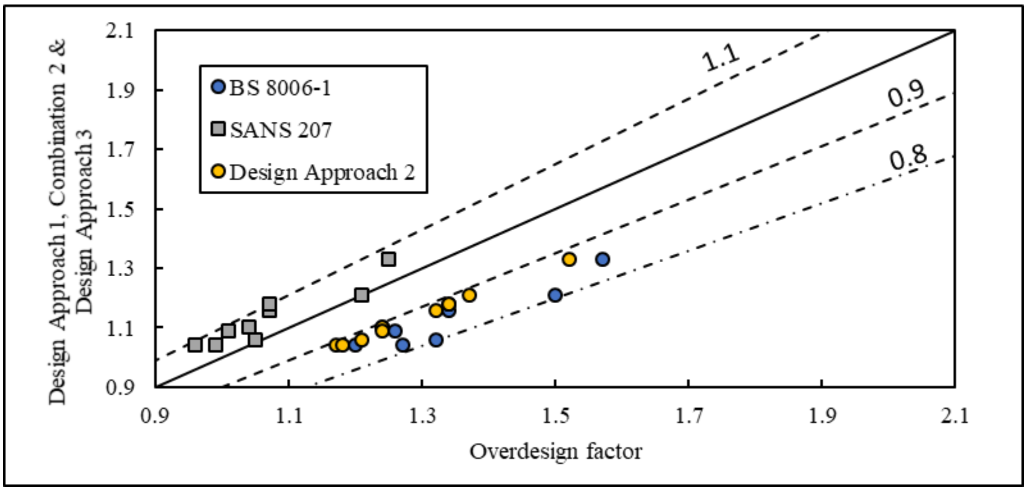

Figure 8: Relationship between overdesign factors from Design Approach 1, Combination 2 / Design Approach 3 and those from BS 8006-1, SANS 207 and Design Approach 2 with a 20kPa surcharge and $r_U = 0.2$

The analysis indicated that of the currently design codes SANS 207 (2006) produced the most conservative designs, which was directly attributable to a moment correction factor, $\chi = 1.25$, currently specified for slip circle analysis in that code. Design Approach 1, Combination 2 and Design Approach 3, which are identical for geotechnical applications, were the next most conservative. Both these are action and material factor approaches, with partial factors applied simultaneously to the actions and material parameters. In particular, they apply a factor of 1.25 to tan of the angle of friction which has a significant influence over the resultant overdesign factor for reinforced soil slopes.

Replacing SANS 207 (2006) with a Eurocode 7 approach is likely to result in more economic reinforced soil slopes, with the economic benefit dependent on which design approach is ultimately adopted.

Updating BS 8006-1 (2010) to include Design Approach 1 for the design of reinforced soil slopes could increase the conservatism of UK reinforced soil slopes. The analysis presented here indicates that Design Approach 1 was more conservative than the BS 8006-1 (2010). This could increase the cost of constructing reinforced soil slopes in the UK.

REFERENCES

Anon (2016). http://eurocodes.jrc.ec.europa.eu/doc/Moscow08/Moscow08_10_Greenley.pdf, Retrived 20th May 2016.
British Board of Agément, BBA Certificate No. 98/R098 Product Sheet 1, Linear Composites‘ Soil Reinforcement Products: Paragrid Geocomposite.
Bond, A & Harris, A. (2008). Decoding Eurocode 7. Taylor & Francis, London.
BS 8006 (1995). Code of practise for strengthened/reinforced soils and other fills. British Standards Institution, UK.
BS 8006-1 (2010). Code of practise for strengthened/reinforced soils and other fills. British Standards Institution, UK.
EBGEO (2011). Recommendations for design and analaysis of earth structures using geosynthetics reinforcement – EBGEO. The German Geotechnical Society.
EN 1997 (2004). Geotechnical design – Part 1 General rules. CEN, Brussels.
Maccaferri (2010). Maccaferri Stability Analysis of Reinforced Soils and walls Software, MacStar W. Officine Maccaferri, Bologna, Italy.
SANS 207 (2005). The design and construction of reinforced soils and fills. Standards South Africa.