A COMPARISON OF NATIONAL DESIGN STANDARDS FOR THE DESIGN OF REINFORCED SOIL RETAINING WALLS

P. Thurlwell
Tensar International Ltd., Blackburn, Great Britain

O. Naciri
Tensar International Gmbh, Bonn, Germany

T. Huybregts
Tensar International B.V., s'Hertogenbosch, Netherlands

ABSTRACT: A number of national design codes of practice for reinforced soil have been developed since the publication of BS8006. National Design Standards describe different design procedures with each reflecting the particular preferences of each country. This paper takes some standard reinforced soil wall dimensions and compares the resulting reinforcement requirements. With the harmonisation of standards in the form of CEN or ISO documents being very high on the agenda it is important to be aware of the difference in output from the range of national documents. There is no doubt that a harmonised design code will be required and this paper should help to provide the foundation for collaboration and co-ordination between the national bodies to ensure a complete and universally accepted document in the future.

1 INTRODUCTION

The use of geosynthetic materials to reinforce soil structures has seen as significant increase in recent years, particularly with respect to reinforced soil retaining walls. A number of national codes of practice for reinforced soil retaining wall design now coexist. The design principles within each code are in general agreement however the application of the design methods, material values and factors of safety vary considerably. This variance tends to arise from an attempt within each code to conform to existing national standards and prescribed safety factors.

2 DESIGN METHODS

Three national codes will be examined in detail to identify the similarities and the differences. Three retaining wall heights will be designed to each code and the resulting reinforcement requirements compared.

2.1 *Fundamental principles of the design*

2.1.1 *British Standard BS 8006*

British Standard BS8006 was initially published in 1995 with an amendement issued in 1999. The Standard uses a limit state format and details reinforced soil design methods for retaining walls, steep slopes, and weak foundations. Also detailed within the standard are sections dealing with the determination of material design properties, including geosynthetic strength, testing for design purposes, and construction techniques. Two methods are detailed for the design of reinforcemed soil walls: Tie-Back Wedge method for extensible reinforcement, and Coherent Gravity method for inextensible reinforcement. The limit state format Tie-Back Wedge method is an extension of the long established limit equilibrium method.

External and internal modes of failure are considered in the analysis as follows:

External Stability:

- Bearing and tilt failure
- Forward sliding
- Overall slip circle failure

Internal Stability:

- Local rupture of individual reinforcement layers
- Adherence capacity of reinforcement
- Sliding through the structure
- Wedge stability within the reinforced fill

For each mode of failure partial load factors are applied to the actions (disturbing forces) to increase their values and partial material factors are applied to the resistances (restoring forces) to reduce their values. Hence the soil weight and live loads are increased and the soil properties and reinforcement strengths are reduced. Soil strengths are based on peak values. As well as applying partial load and material factors additional factors of safety are applied to the bearing capacity, sliding and pull-out calculations.

Three load cases are defined to ensure that the most adverse load combinations likely to be applied to the structure are considered in the design. Load cases A and B apply to the Ultimate Limit State whilst Load Case C applies to the Serviceability Limit State; i.e. reinforcement strain and foundation settlement. The specified partial factors are detailed in Table 1 and 2 below.

Load Case A considers the maximum values for all loads and is usually critical for bearing capacity, reinforcement rupture, and wedge stability.

Load Case B considers the maximum overturning and minimum self mass of the structure and is usually critical for sliding and pull-out resistance.

Load Case C considers dead loads only in the working condition and is used to determine the performance of the structure (settlement, creep, reinforcement strain).

2.1.2 *German design standard EBGEO*

The first German recommendations, EBGEO, for the design of the reinforced soil structures (vertical walls, steep slopes, embankment basal reinforcement, foundations, soil stabilisation, and landfill) were published in 1997. These were based on the German Norm 1054-100 (4/96) after the partial safety factor concept. This was the first written recommendation. However, Norm 1054-100 (4/96) was never put into practice. EBGEO is currently in the process of revision based on a new German Norm 1054 (01/03) that was published in January 2003. The following description and the example is made following this new German Norm 1054 (01/03).

This norm is based on the use of limit state methods by use of the partial safety factors. The reinforced soil wall calculation needs to satisfy the ultimate limit state ULS (GZ 1) and the serviceability limit state SLS (GZ 2).

Figure 1 details all the modes of failures that need to be satisfied in accordance with DIN 1054 (01/2003).

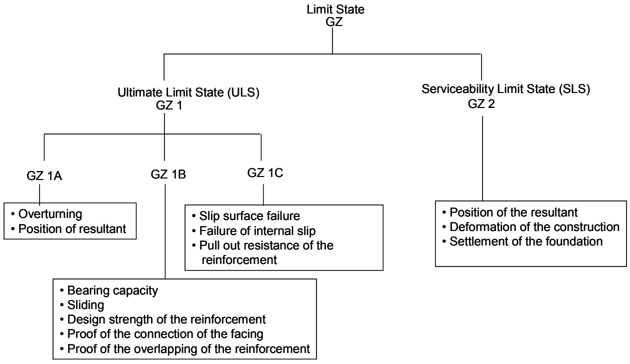

Figure 1: Limit state after DIN 1054 (01/2003)

The ULS GZ1B describes the failure of structure and construction components. This ULS-check is required to verify the following fundamental condition:

$$E_d = E_k(\varphi_k, c_k, \gamma_k) \cdot \gamma_E \le R_d = \frac{R_k(\varphi_k, c_k, \gamma_k)}{\gamma_R}$$

where the action effects E_k and the resistance R_k are determined with characteristic values. The design value E_d is obtained by multiplication of the characteristic values E_k with the partial factors γ_E, recommended by German Norm 1054. The design values of the resistance R_d are determined by the division of the characteristic values R_k by the partial factors γ_R. The specified partial factors are detailed for load factor 1 in Table 1 and 2 below.

The ULS GZ1C describes the overall stability failure of the structure. The design values of the action effects E_d and resistance R_d for this state are determined from the design parameter of the strength of the soil.

$$\begin{pmatrix} \varphi_k \\ c_k \\ \gamma_k \end{pmatrix} \rightarrow \begin{pmatrix} \varphi_d = (\arctan \varphi_k)/\gamma_\varphi \\ c_d = c_k / \gamma_c \\ \gamma_d = \gamma_k \cdot \gamma_G \end{pmatrix} \rightarrow E_d(\varphi_d, c_d, \gamma_d) \le R_d(\varphi_d, c_d, \gamma_d)$$

2.1.3 *Dutch design recommendation CUR 198*

In view of the increasing use of reinforced soil structures in the Netherlands and the various methods of calculation used by suppliers of such systems, clients required guidance on the most appropriate design method. Therefore in September 2000 a new design recommendation was published called CUR-publication 198 "Kerende constructies in gewapende grond" [*Retaining structures in reinforced soil*]. The method of analysis is similar to other methods and comprises checks on the external and internal stability. For the internal check the method of analysis is dependent on the type of reinforcement used. For inextensible reinforcement the Coherent Gravity method is used and for extensible reinforcement the Tie-Back Wedge method is used.

This new design recommendation is based on a probabilistic failure analysis and uses the Dutch partial safety factors according to NEN 6700 series for the external stability analysis. For the internal stability analysis the CUR publication provides the partial safety factors (material factors, load factors and method factors).

The analysis has to satisfy both the Ultimate Limit state (Case A and B) and the Serviceability Limit state.

There is a difference in the application of the partial safety factors between the external and internal stability analysis. The external stability is checked in a similar way to the EBGEO method. For the check of the internal stability the disturbing forces are calculated based on the design values for the internal frictional angle (φ_d) and the cohesion (c_d), multiplied by the additional load factors (γ_G and γ_Q). Soil strengths are based on constant volume values.

$$\begin{pmatrix} \varphi_k \\ c_k \\ \gamma_k \end{pmatrix} \rightarrow \begin{pmatrix} \varphi_d = (\arctan \varphi_k)/\gamma_\varphi \\ c_d = c_k/\gamma_c \\ \gamma_d = \gamma_k \end{pmatrix} \rightarrow \begin{pmatrix} \text{Soil Earth pressure } E_{agh,k} \\ \text{Surcharge Earth pressure } E_{aqh,k} \end{pmatrix} \rightarrow \begin{pmatrix} E_d = E_{agh,k} \cdot \gamma_G \\ E_d = E_{aqh,k} \cdot \gamma_Q \end{pmatrix}$$

This differs from both the other methods and also from the Dutch standard itself. The method in this new recommendation, using the specified partial safety factors, is checked in order to investigate whether the design leads to an acceptable safety level in accordance with Dutch standard NEN 6700.

Table 1 : Partial Factors for actions (effects)

	BS 8006 Combination A	BS8006 Combination B	BS8006 Combination C (SLS)	EBGEO Limit state 1B	EBGEO Limit state 1C	EBGEO Limit state 2 (SLS)	CUR198 Limit state Case A	CUR198 Limit state Case B	CUR198 Serviceability limit state
Permanent effect – mass of reinforced soil body	ffs=1.5	ffs=1.0	ffs=1.0	γ_G=1.35	γ_G=1.0	γ_G=1.0	γ_G=1.2	γ_G=0.9	γ_G=1.0
Permanent effect – earth pressure behind the structure	ffs=1.5	ffs=1.5	ffs=1.0						
Unfavourable variable effect	fq=1.5	fq=1.5	fq=0	γ_Q=1.5	γ_Q=1.3	γ_Q=1.0	γ_Q=1.5	γ_Q=1.5	γ_Q=1.0

Table 2 : Partial Factors for resistances

	BS 8006 Combination A	BS8006 Combination B	BS8006 Combination C (SLS)	EBGEO Limit state 1B	EBGEO Limit state 1C	EBGEO Limit state 2 (SLS)	CUR198 Limit state Case A	CUR198 Limit state Case B	CUR198 Serviceability limit state
Soil resistance	-	-	-	γ_{EP}=1.4					
Foundation Bearing capacity	fms=1.35	fms=1.35	N/A	γ_{Gr}=1.4					
Sliding along a base	fs=1.2	fs=1.2	N/A	γ_{Gl}=1.1					
Reinforcement material factor	Variable	Variable	Variable	γ_B=1.4			BBA certificate	BBA certificate	BBA certificate
Soil material Factors: - to be applied tan φ - to be applied to c`	fms=1.0 fms=1.6	fms=1.0 fms=1.6	fms=1.0 fms=1.0		γ_φ=1.25 γ_c=1.25		γ_φ=1.2 γ_c=1.5	γ_φ=1.2 γ_c=1.5	γ_φ=1.2 γ_c=1.5
Pull-out resistance	fp=1.3	fp=1.3	fp=1.0		γ_B=1.4		γ_{aanh}=1.0	γ_{aanh}=1.0	γ_{aanh}=1.0

2.2 *Comparison of the design strength of the reinforcement*

Each of the three design codes determines the reinforcement design strength in a different way.

BS8006 reduces the base strength of the reinforcement by a number of partial factors of safety to derive the design strength:

$$T_D = \frac{T_{cr}}{f_{m11} \times f_{m121} \times f_{m122} \times f_{m211} \times f_{m212} \times f_{m22} \times f_n}$$

fm11 consistency of manufacture
fm121 sufficient data to derive 'statistical envelope'
fm122 extrapolation of 'statistical envelope'
fm211 short term damage effects
fm212 long term effects of short term damage
fm22 environmental effects (chemicals, UV)
fn ramification of failure

The base strength is either the creep rupture strength for the ultimate limit state or the creep limited strain for the serviceability limit state, both measured at the end of the design life. All partial factor values are self-certified.

Within EBGEO the design strength ($F_{Bi,d}$) of the reinforcement is based on the following formula:

$$F_{Bi,d} = \frac{F_{Bi,k0}}{A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot \gamma_B}$$

$F_{Bi,k0}$: short term strength of the geogrid per metre width
A1: reduction factor for long-term strength
A2: reduction factor for damage during installation and compaction factor
A3: reduction factor for connection and overlapping
A4: Environmental reduction factor
γ_B: Material factor of safety

CUR198 determines the design strength of the material using the same partial factors for the reinforcement as detailed in BS8006. The partial factor values are determined according to BBA (British Board of Agrément) certificates for the reinforcement material.

The design strength of Tensar 80RE geogrid for the ultimate limit state condition determined in accordance with the 3 codes is shown in Table 3.

Table 3 : Design strength of 80RE (ULS)

	BS8006	EBGEO	CUR198
Design strength (fill with 75mm particle size)	30.2kN/m	23.76kN/m	26.09kN/m

2.3 *Design Example: Comparison of design methods*

For this exercise three vertical walls of height 10 m, 8 m, and 5 m have been considered as representative for analysis.

Each design is based on the use of Tensar RE range of HDPE geogrids. A practical maximum of three grades of geogrid have been selected for use in the analysis. The maximum vertical spacing between geogrids is set as 0.6 m. The design strength will be based on the use of a fill with a maximum particle size of 75 mm. The joint between the geogrid and the facing is taken as a full strength connection.

A live traffic load surcharge of 10 kN/m² will be considered.

The soil parameters used within the analysis are shown in Table 4:

Table 4: Soil parameters

	Friction angle		Cohesion [kN/m^2]	Unit Weight [kN/m^3]
	Peak φ`$_p$ [°]	Constant volume φ`$_{cv}$ [°]		
Reinforced fill	36	30	0	20
Backfill	36	30	0	20
Foundation	30		0	18

2.4 *Results*

The required minimum geogrid reinforcement length for each wall height as determined from the external stability analysis is detailed in Table 5:

Table 5 : Required geogrid length

Wall Height	Geogrid Length		
	BS8006	EBGEO	CUR198
10m	7.0m	7.0m	7.0m
8m	5.6m	5.6m	5.75m
5m	3.5m	3.5m	3.75m

External stability is generally based on classic retaining wall analysis and therefore the similarity of the results would be expected.

The internal stability of the structure is generally assessed in a similar manner within each code however the resulting stresses, strains, and reinforcement design strengths are determined using dissimilar partial factors of safety.

As each method uses different design strengths the ultimate capacity of the geogrid reinforcement will be used to compare the required quantities of reinforcement. Table 6 details the total combined ultimate strength of all geogrid layers within the design.

Table 6 : Required geogrid strength

Wall Height	Ultimate Strength Requirement		
	BS8006	EBGEO	CUR198
10 m	1811 kN/m	1739 kN/m	2051 kN/m
8 m	1243 kN/m	1195 kN/m	1355 kN/m
5 m	587 kN/m	587 kN/m	651 kN/m

The reinforcement requirements of all 3 codes are similar for low height walls however as the wall height increases the quantity of reinforcement required for stability diverges. For the 10 m high wall EBGEO produces slightly lower (4%) reinforcement requirements than BS8006, whereas the CUR198 is up to 13% higher as BS8006.

Although there is significant variation in the partial factor values and design strengths, within each code the resulting geogrid requirements are generally similar. The CUR198 produces the greatest quantity of reinforcement, which is probably the result of the application of double load factors, one to reduce the characteristic soil values to design values and an additional load factor applied to the resulting earth pressure.

The resulting distribution of ultimate geogrid strength with depth is detailed in Fig 2 for the 10m wall height. The resulting strength at each layer has been converted to a strength requirement per m^2 of wall face based on the effective vertical spacing between the resulting geogrid layers.

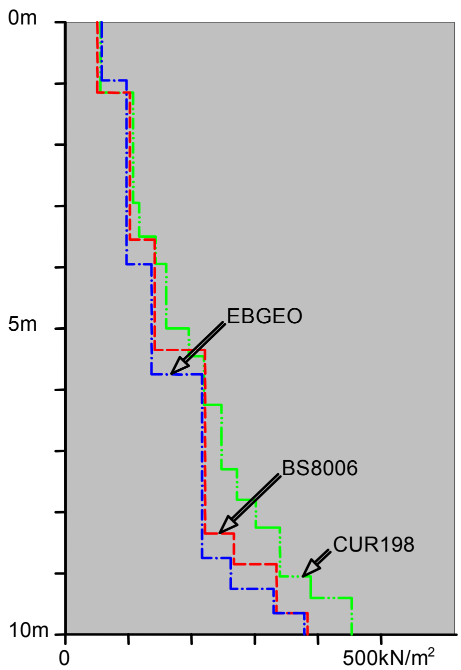

Figure 2: Resulting distribution of ultimate geogrid strength per m^2 of wall face against depth for the 10m wall height

Figure 3 details the cumulative ultimate strength requirement per m^2 of wall face against depth within the wall with a height of 10 m.

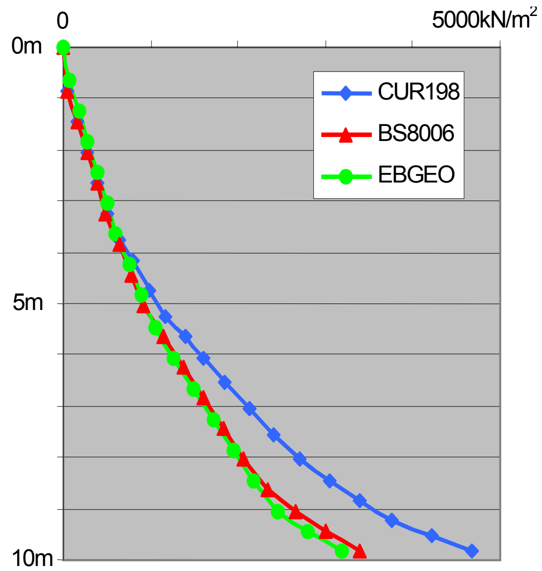

Figure 3: Cumulative ultimate strength requirement per m² of wall face against depth

3 CONCLUSION

Three national codes (BS8006, EBGEO, CUR198) have been examined in detail in order to identify their similarities and differences. All three designs are based on the limit state. In the first part of the article, the fundamental principles of the design for each code has been described, particularly the partial factors and the design strengths. The practical and economic differences between the design methods have been examined by performing three example calculations.

The reinforcement requirements of all 3 codes are similar for low height walls however as the wall height increases the quantity of reinforcement required for stability diverges. Although there is significant variation in the partial factor values and design strengths within each code the resulting geogrid requirements are generally similar. The CUR198 produces the greatest quantity of reinforcement, which is probably the result of the application of double load factors, one to reduce the characteristic soil values to design values and an additional load factor applied to the resulting earth pressure.

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