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Citation: FROST, M.W. ... et al, 2012. Serviceability limit state design in geogrid reinforced walls and slopes. Presented at EuroGeo5: the 5th European Geosynthetics Congress, 16th-19th September 2012, Valencia, Spain.

Additional Information:

- This is a conference paper.

Metadata Record: https://dspace.lboro.ac.uk/2134/11629

Version: Accepted for publication

Publisher: International Geosynthetics Society (IGS)

Please cite the published version.

Serviceability limit state design in geogrid reinforced walls and slopes

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Keywords: geogrid, serviceability, deformation

ABSTRACT: The design of geogrid reinforced walls and slopes, although a well-established science, still contains many unknowns, particularly around long-term serviceability. Serviceability, for walls and slopes, is associated with excessive deformation or damage affecting appearance, maintenance or service life. In most designs, the serviceability limit state is not considered critical. Currently, most serviceability checks do not attempt to determine or prescribe deformation limits on the built wall or slope, but rather impose limits on the theoretical mobilised strains of geogrid reinforcement, considering the unfactored imposed loads. In many cases, these prescribed post-construction allowable strain limits are based on long-term, or accelerated creep testing, undertaken when the geogrid is not interacting with soil. In some situations, designs are grossly over-conservative. This paper reviews the current state of practice, summarising some of the serviceability design issues around geogrid reinforced walls and slopes, with a particular focus on long-term post-construction deformations. The paper goes on to highlight areas of non-conformity in serviceability design, between the major national codes in Europe, assessing their strengths and weaknesses. Additionally, the paper highlights potential areas of on-going and further work that may offer a better understanding of the serviceability limit state of geogrid reinforced soil walls and slopes.

1 INTRODUCTION

Soil-retaining structures (SRSs) are a solution to stabilise slopes, where unreinforced slope construction is uneconomical or not technically feasible. SRSs prevent backfill soil from assuming its natural slope angle. Geogrid reinforced soil-retaining structures (GRSRSs) provide an economic alternative to mass concrete and other SRSs. GRSRSs typically consist of several components (Figure 1): Geogrid reinforcement; Reinforced soil fill; Retained backfill soil; Foundation soil and an optional facing component, providing local support to the reinforced soil fill (e.g. segmental blocks, concrete panels, wraparound etc.).

Serviceability is often overlooked when designing GRSRSs, with the emphasis on ultimate limit state failures. Conversely a report by Koerner and Koerner (2009) found 23 of 82 reported GRSRS failures were considered to have exceeded their serviceability performance limit, by excessively deforming. GRSRSs are often over-conservative because their internal mechanisms are so poorly understood. This paper reviews the current state of SLS design, comparing the UK's design code with the German counterpart, summarising issues with current understanding and practice; finally making a number of broad recommendations, to improve design to reflect current understanding.

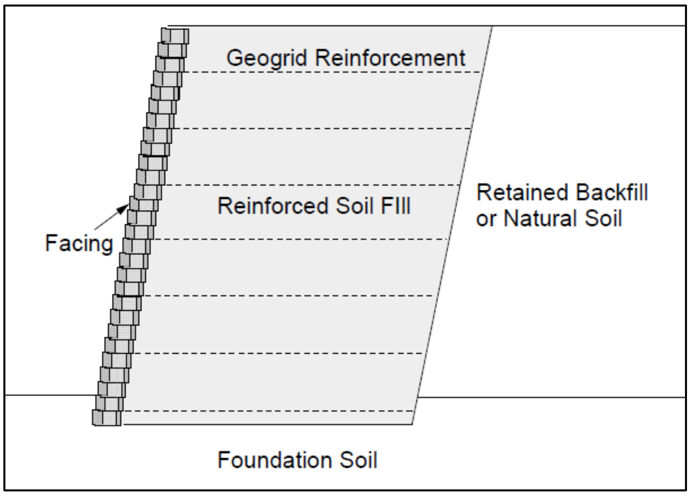

Figure 1. Typical Components in a GRSRS

2 SLS DESIGN

When designing structures a number of limits are defined, beyond which the structure no longer satisfies design performance requirements. In design codes these limits are broken down into ultimate limit states (ULSs) and serviceability limit states (SLSs). ULSs are generally associated with collapse or structural failure, while SLSs correspond to unacceptable deformations or other types of damage, increasing maintenance requirements or reducing service life. Deformation in a structure can occur during construction or post-construction. Although the former is not considered in this paper, it is widely acknowledge that quality assurance practices, such as good compaction, help reduce its effects. Examples of post-construction deformation failures are displayed in Figure 2.

There is a great deal of non-conformity amongst the various national codes throughout Europe, as currently the Eurocode for geotechnical design, EN 1997 (British Standards Institute, 2004), does not cover the design and execution of GRSRSs, according to the UK national annex (British Standards Institute, 2007a). Instead, design is determined by individual codes, the most common are BS 8006 (British Standards Institute, 2010) and EBGEO (Deutsche Gesellschaft fur Geotechnik, 2011).

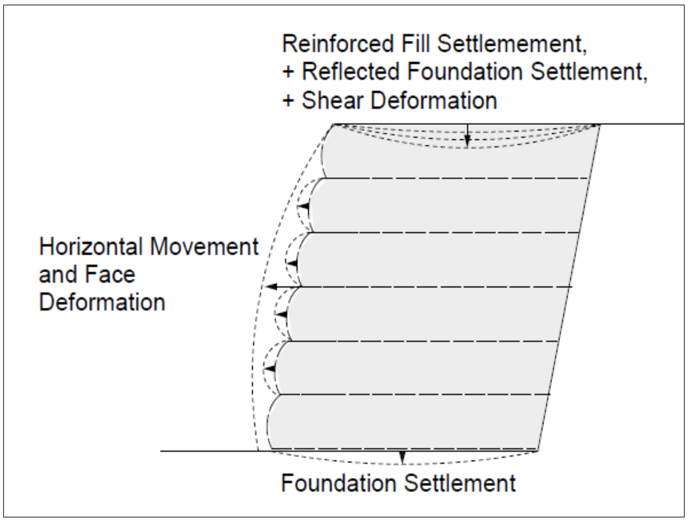

Figure 2 . Sources of post-construction deformation in a typical GRSRS according to EBGEO (2011).

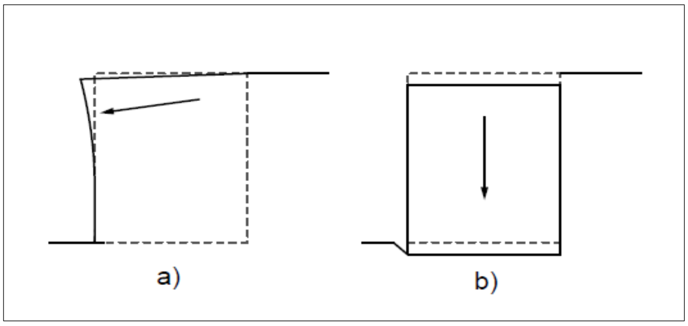

Figure 3. Serviceability Limit States according to BS 8006 (2010): a) Wall Deformation; b) Settlement.

2.1 *BS 8006 (2010)*

In the UK, the principal design code for the design of reinforced soil structures is BS 8006 (British Standards Institute, 2010), herein referred to as BS 8006 (2010). The code defines structures with gradients up to 70° as slopes, while steeper structures are defined as walls, designed as vertical structures. The code provides initial dimension guidelines, before assessing the following external ULSs: bearing and tilt failure, forward sliding and overall slope stability; followed by internal ULSs, using the *Tie-back wedge method* for walls, or well-established slope stability methods (e.g. *slip circle analysis*), derived from unreinforced structures, for slopes.

BS 8006 (2010) recommends SLSs (Figure 3) are checked to ensure the structure will fulfil its function throughout its design life, without the need for abnormal maintenance. SLS analysis, considers only characteristic dead loads. BS 8006 (2010) recommends checks are performed on the following SLSs:

2.1.1 *Settlement of the foundation*

This limit involves investigating the consolidation of the foundation over the lifetime of the structure. This can be calculated using conventional soil mechanics approaches, directing the designer back to EN 1997 (British Standards Institute, 2004).

2.1.2 *Post-construction creep of saturated fine grained soils*

Determining post-construction creep of saturated fine grained soils analytically is very complex, consequently consideration should be given to provide good drainage and/or sealing of the reinforced zone.

2.1.3 *Geogrid post-construction creep deformation*

BS 8006 (2010) prescribes a limit on the internal post-construction strain occurring between the end of construction and the end of the design life. This is limited to 1% in walls (non-abutments) and 5% in slopes. The restricted tensile capacity of the geogrid, T_{cs} is obtained using isochronous load-strain curves (Figure 4), before reducing this value to the SLS design strength T_D using equation 1.

$$T_D = \frac{T_{CS}}{f_m} = \frac{T_{CS}}{RF_{ID} \cdot RF_W \cdot RF_{CH} \cdot f_s} \tag{1}$$

Where: RF_{ID} = reduction factor (RF) for installation damage; RF_W = RF for weathering; RF_{CH} = RF for chemical and environmental effects; f_s = factor of safety for the extrapolation of data. These factors are determined in accordance with PD ISO/TR 20432 (British Standards Institute, 2007b). SLS design strength is finally checked against the expected geogrid tensile forces, under service loading conditions.

2.1.4 *Wall Deformation*

BS 8006 (2010) provides descriptive guidance on wall deformation or horizontal movement suggesting vertical spacing of reinforcements should be limited to prevent local surface failures such as bulging.

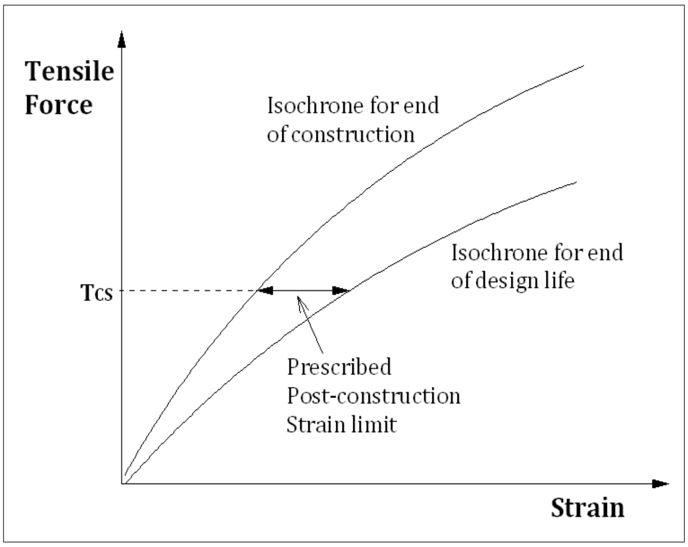

Figure 4. Typical isochronous curve used for restricted service tensile stress capacity. Adapted from BS 8006 (2010).

2.2 *EBGEO (2011)*

The German design code, *Recommendations for Design and Analysis of Structures using Geosynthetic Reinforcements*, EBGEO (Deutsche Gesellschaft fur Geotechnik, 2011), herein referred to as EBGEO (2011), is based on the *German National Standard for Earthworks*: DIN 1054 (Beuth, 2005). EBGEO (2010) starts by assessing ULSs, before considering SLSs which it defines as structural deformations resulting from characteristic dead loads and soil parameters. The code highlights the following SLSs (Figure 2): foundation settlement; internal settlement of reinforced fill; horizontal movement of the front of the structure and face deformation. Each component may be estimated using numerical analysis, empirical data or observational methods, except for the most trivial structures.

2.2.1 *Horizontal Movement of Structure*

EBGEO (2011) suggests a general analytical method of integrating individual strains to obtain a total horizontal deformation, for given tensile forces in the geogrid layers. The designer can calculate this from the service loading and the load-strain characteristics of an individual geogrid.

2.2.2 *Shear Deformation*

The horizontal movement of the structure will subsequently cause counter settlement at the surface as material is displaced outward. EBGEO (2011) suggests this can be determined using empirical data.

2.2.3 *Foundation Settlement*

As with BS 8006 (2010), the German code directs designers to an additional design code for earthworks, DIN 4019 (Beuth, 2005), suggesting GRSRS may act as a flexible load area on the foundation.

2.2.4 *Reinforced Fill Settlement*

EBGEO (2011) proposes most reinforced fill settlement will take place during construction, at least for granular fill, providing some general empirical data for typical settlements.

2.2.5 *Face Deformation*

The German code suggests examining the forces present on the face and the subsequent deformation, without giving a detailed design method beyond using the active earth pressure as a reference variable.

2.3 *Design Comparison*

Comparing the two codes, BS 8006 (2010) offers more prescriptive methods for SLS design. The German code is proficient in conventional designs but becomes more difficult for innovative projects, where less empirical information is available. EBGEO (2011) accounts for the possible sources of deformation, more comprehensively than BS 8006, although in most cases it lacks detailed methodologies.

The most notable contrast between BS 8006 (2010) and EBGEO (2011) is in their assessments of horizontal movement. BS 8006 limits the internal post-construction strain of geogrids, while EBGEO suggests integrating the strains in each layer of reinforcement and calculating a total deformation. This assumes the soil and geogrid deform in unison. Both use theoretical mobilised strain values for reinforcement, as reliable data for reinforced soil compatibility is currently unavailable.

EBGEO (2011) does not currently give any guidance on the use of reduction factors (RFs) for SLS design; therefore not detailing the effect that installation and chemicals have on use of isochrones and subsequently long-term in-service design strength. BS 8006 (2010) applies arbitrary limits on the post-construction strain of geogrid to its two categories of structures. For example, allowable post-construction strain limits for structures with gradients of 69° and 71° are 5% and 1% respectively.

Design should assess SLSs such as differential settlement and bulging of the face, determining deformations in units of length, however current analytical methods make it difficult to do this.

3 ISSUES OF UNDERSTANDING

Several reviews have been compiled, monitoring post-construction deformation of GRSRSs (Allen *et al.*, 2002; Bussert and Naciri, 2008), revealing grossly over-designed structures, where deformations are much smaller than expected. This suggests problems with our current understanding of GRSRS.

3.1 *Composite Material Behaviour*

Current design codes base their analytical methods on the *Simple Method* (Allen, *et al*., 2002): using only geogrid or soil properties of reinforced soil, rather than composite properties because they are more obtainable. The composite material displays different material characteristics than unreinforced soil, such as additional confining stress, contributing to extra load carrying capacity (Bussert 2008). Confinement increases soil shearing resistance and young's modulus, creating a stiffer material and reducing deformations. Deformation compatibility of reinforced soil is not homogenous and is more complex than current methods suggest. The long-term creep reduction of geogrid strength may also be excessive. Franca and Bueno (2011) used pioneering laboratory equipment to confirm a significant reduction in creep in the composite material, compared to the geogrid alone (in-air).

3.2 *Vertical Stress Distribution*

Although the methods for analysing foundation settlement are well-established throughout geotechnical engineering, there have been studies (Yang *et al.,* 2010) to suggest vertical pressure from the reinforced soil acting on the foundation is more complex than our current understanding, depending significantly on the flexibility of facing in the structure.

3.3 *Lateral Earth Pressure*

Corresponding to the observed discrepancies in vertical stress (Yang *et al.,* 2010), variations in observed horizontal stresses have also been observed as non-linear and consistently less than expected by current design. This may be explained in-part by Ruiken *et al.* (2010), who observed that geogrids reduce the horizontal pressure in the soil, but this has yet to be incorporated into designs. They noticed a reduction in horizontal stress as more layers of geogrid were incorporated. For facing deformation design, only the active earth pressure of soil is considered, without any geogrid reducing effects. Therefore the horizontal design pressure acting on the back of the facing is over-estimated.

3.4 *Reinforcement Strain Distribution*

Under current design, strain distribution along the reinforcement is considered to be uniform as a result of uniform vertical stress conditions; however as acknowledged in Sections 3.2 and 3.3, non-linear stresses induce a non-linear strain distribution in the reinforcement as observed by Onodera *et al.* (2004), Bussert and Naciri (2008) and Yang *et al.* (2010) amongst others. Integrating strain distribution better accounts total deformation of the geogrid, because it more accurately accounts the whole distribution, unlike the limit on strain as used in BS 8006 (2010).

3.5 *Reduction Factors*

In both codes, the understanding of RFs can be improved. Currently they both use partial factors that assume loading starts after the reinforcement has been completely degraded. Additionally RFs are determined individually and subsequently combined. Work by Kongkitkul *et al.* (2007) suggests this process underestimates long-term strength, as creep and chemical degradation act simultaneously over the lifetime of the structure, which is affirmed by tests (Onodera *et al.*, 2004) on excavated samples which found higher retained strengths, than are calculated by current design.

4 ISSUES OF PRACTICE

A major source of conservatism in GRSRSs results from simplified designs for specification, manufacture and construction, which result in much more geosynthetic reinforcement than required for acceptable performance. Allen and Bathurst (2002) amongst others have called on designers to adopt a more aggressive approach to the selection of materials and reinforcement spacing; closely matching reinforcement strength to demand. However, in reality this is difficult to achieve as geogrid suppliers offer reinforcement strengths in step changes to obtain economies of scale. Additionally geogrid spacing is often dictated by the height of the facing elements adopted.

5 RECOMMENDATIONS

Throughout the review, it has been established that current SLS design is not as comprehensive as ULS design, highlighting many areas where understanding can be improved. Design codes currently use over-simplified methods to design GRSRSs. For SLS design to be improved, analytical models must be updated to accurately represent the forces developed in the reinforced soil, integrating the full strain distribution, as highlighted in EBGEO (2011). Limiting post-construction geogrid strain is not sufficient to calculating deformation. Any updated method should include the properties of the composite material within current technology limitations. Design should also account for deformable and non-deformable facing types that influence how stress is distributed within the structure. There are of course limitations in the current technology in determining accurate properties for soil/grid composite behaviour.

This review has highlighted various opportunities to improve the accuracy of these methods, although in turn, these changes will increase the complexity of designs, making them less accessible. Ultimately, the industry will decide where the balance lies between economy and complexity. However, the use of marginal fills in reinforced design solutions, and the benefits this brings for improved sustainability, will be constrained if agreed analysis methods, which accurately predict deformation behaviour, are not available to assess SLSs.

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