THE DESIGN OF GEOSYNTHETIC SOIL RETAINING STRUCTURES WITH VARIABLE ANGLE LATERAL BOUNDARIES

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Abstract: This paper deals with the age old questions: When does a soil retaining structure become a wall, when is it seen as a steep slope, and what analytical approaches are available and should be used to design them? The introduction of non-linear (variable angle) lateral boundary geosynthetic reinforced soil slopes and walls together with the Limit State approach to design, makes these questions all the more relevant. Thus consideration is given in this paper to the following: (i) What defines a steep slope and a wall; (ii) What are the benefits of non-linear (variable angle) lateral boundaries; (iii) Is there a better, more integrated approach using FEM or similar modern numerical approaches; and (vi) Which Factors of Safety, Material Safety Factors or Partial Factors are appropriate for design? In posing these questions, this paper aims to raise discussion on the current design approach methodologies to geosynthetic reinforced steep slopes and walls.

Keywords: slope, reinforced slope, reinforced soil wall, earth pressure, lateral pressure, geogrid reinforcement, limit state design

INTRODUCTION

With the introduction of non-linear (variable angle) lateral boundary geosynthetic reinforced soil structures, geotechnical practitioners are required to decide for design purposes, when a steep slope becomes a wall and vice versa. Slopes are generally stable under self-weight if the slope angle is less or equal to the constant volume effective angle of friction [ϕ'_{cv}]. However, if the slope angle exceeds this, it is termed a steep slope and is considered to be unstable unless some form of support or reinforcement is provided. This can be achieved either by external support, (such as shot concrete facing or the provision of structural facing), or by providing internal reinforcement, (such as soil nails, anchors or geosynthetics). The out of balance forces increase with increasing slope angle and currently a steep slope is considered to become a wall if the slope angle is greater than 70º, Table 1.

Table 1 Current Definitions

Slope	Slope angle $\leq \phi'_{cv}$	Stable
Steep Slope	Slope angle $> \phi'_{cv} \leq 70º$	Reinforced, possibly with a flexible or rigid facing
Wall	Slope angle > 70º	Reinforced and provided generally with a rigid facing

The current choice of a slope angle of 70º to define the change from steep slope to wall is essentially arbitrary. There is no fundamental sudden change in behaviour that occurs at this slope angle. Indeed in the 1970's and 80's it was common practice to define the change from steep slope to wall as occurring at a slope angle of 80º.

However, the distinction between steep slopes and walls is important as most design standards require different analytical approaches for steep slopes and walls and employ different global Factors of Safety, Material Safety Factors and / or Partial Factors.

The out of balance forces may be based on equilibrium conditions within the reinforced fill with no lateral boundary deformations (at-rest conditions), lateral expansion (active conditions) or lateral contraction (passive conditions).

A key assumption in current analyses is that the lateral boundary, i.e. the slope or wall face, is planar, either vertical or inclined. Stepped or terraced lateral faces are used occasionally and represented as equivalent planar boundaries. The introduction of geosynthetic reinforcements has not changed this convention. Thus, for geosynthetic reinforced steep slopes and walls, planar lateral boundaries are generally assumed. In such cases, the lateral earth pressures to be resisted by the geosynthetic increase in proportion to the height of the structure. This can result in rather complicated reinforcement layouts with the spacings, lengths and types varying with depth, and this may result in gross over-provision of reinforcements. In addition, base bearing pressures are generated with a maximum near the toe of the structure and these pressures increase with the height of the structure. This can impose severe limitations on the maximum height of structure that can be constructed using geosynthetic reinforcements.

Thus, in this paper the concepts of lateral earth pressure analysis are briefly reassessed and related to geosynthetic reinforced steep slopes and walls. The concept of non-linear lateral boundaries is introduced. Furthermore, the benefits to be gained from the use of the "true" Limit State approach to design are identified. The paper poses numerous questions and hopefully encourages the re-evaluation of current design practices.

EARTH PRESSURE CONCEPTS

Conventional earth pressure theories employed in the design of Geosynthetic Reinforced Soil Structures, [GRSS], indicate that the magnitude and distribution of lateral earth pressures are dependent upon many factors, including:

- the type of soil used as the reinforced fill (generally coarse granular well graded soil),
- the density of the fill (generally competent fill compacted to 95% MDD [Maximum Dry Density] at ±2% of OMC [Optimum Moisture Content]),
- the magnitude of the soil-facing friction (generally 50 to 65% of the peak angle of friction of the soil),
- the nature and magnitude of the lateral boundary movements (generally rotation over the toe or translation of the base) and
- system geometry.

As the angle of the lateral boundary of the structure reduces, so the lateral earth pressure reduces. Indeed, the earth pressures reduce to zero once the facing angle is less or equal to the operational angle of friction of the soil. By selecting the soil type, the construction process and the nature of the lateral boundary, it would thus appear possible to control the magnitude and distribution of lateral earth pressures developed.

Previous research identified several key factors that influence the magnitude and distribution of lateral earth pressures for both conventional and reinforced soil structures, Yogarajah (1993). The key findings were that the lateral earth pressure distribution is greatly affected by lateral boundary movements, and the compressibility (stiffness) of the facing.

Other researchers addressed the earth pressure distributions within steep slopes. Their findings confirmed that the coefficients of lateral earth pressure (K) are not solely functions of the angle of internal friction, but dependent on a number of other factors, Khan (1999). Numerical analysis and full-scale experimental testing indicated that the lateral earth pressures vary with depth and distance from the lateral boundary, as well as, with overburden pressure and other factors. Closed-form solutions, as well as numerical FEM analysis, have been used to determine the magnitude and distribution of lateral earth pressures for planar lateral boundaries for vertical or near vertical walls and for steep slopes.

On these bases it is suggested that, to date, the lateral boundary has been considered to be a fixed parameter, either vertical, inclined or stepped. However, if the facing slope angle is varied with height in the range ϕ'_{cv} to 90°, the earth pressure distribution will not conform to conventional patterns, either in magnitude or distribution. Indeed, by varying the angle and shape of the lateral soil-wall boundary, both the levels and the distribution of the earth pressures may be controlled, Kupec (2004).

DESIGN APPROACHES

At the time of the introduction of GRSSs into modern civil engineering practice during the 1970's, design methods were based on the Limit Equilibrium approach. Many of these design methods utilised a number of empirical assumptions and large global Factors of Safety were employed to ensure that collapse did not occur. One outcome of this approach applied to GRSSs, is that very few failures have occurred due to geosynthetic reinforcement rupture. However, despite using this design approach and very conservative input parameters, the outcome designs are still generally more economic than conventional geotechnical solutions. Thus, GRSSs have become widely accepted in practice.

To date, two main design approaches are currently used in the design of GRSSs. The first and most widely employed remains the Limit Equilibrium approach. Many product specific design methods employ this particular design approach due to its simplicity and proven practice. The other is based on Limit State principles, but includes aspects of the Limit Equilibrium approach and is therefore termed the Hybrid (Transitional) approach. To date, no national or international standard is known to employ 'true' Limit State design principles.

The Limit Equilibrium Approach

Commonly, Limit Equilibrium methods generally represent the soils by their Angle of Friction [ϕ'] and the geosynthetics either by a factored short-term or a factored long-term rupture strength. Sometimes the peak angle of friction is employed as derived from shear box testing, however, the angle of friction at constant volume is equally common. No direct deformation analysis of the GRSS during its service life is considered. Material Safety Factors are often applied to the properties of both the soils and the geosynthetics, as well as, large global Factors of Safety being applied to the overall stability analysis. The Material Safety Factors and global Factors of Safety also ensure that deformations under operational conditions are not excessive.

In addition to the above, all imposed loads are assumed to be either static or quasi-static and to act in a sustained manner over the whole design life. The sum of load combinations that the structure may support without failure or collapse, are called Design Loads, and are equated with the sum of all loads under operational conditions, called Working Loads. Solutions are often obtained by simple static calculations, assuming failure surfaces of various shapes, such as planar, circular, or log-spiral, and by using simple failure criteria. Such Limit Equilibrium methods prove to be very conservative, Berg et al (1998), and so very few failures occur, Giroud (1999).

The Limit State Approach

For the Limit State approach to the design of GRSSs, performance criteria during the period of construction and over the design life require to be set. Thus, when a structure, part of a structure or component operates at a level equal to any of the performance criteria, it may be said to have reached a Limit State. Limit states used in GRSSs designs are conventionally divided into two categories. Firstly, the Ultimate Limit States [ULS], which are concerned with safety, loss of static equilibrium or rupture of either a critical component or the entire structure. Secondly, Serviceability Limit States [SLS], which are conditions, or performance criteria, beyond which the functional or aesthetic utility of a component, or the entire structure, is lost. Importantly, for GRSSs, the loss of serviceability may be due to either internal or external factors, e.g. internal component failure or external ground deformations.

Limit State design requirements for geotechnical structures were set by Eurocode 7 (1995). This code recognises three main categories, classified according to the involved risks and the complexity of the geotechnical analysis. Consequently, design methods based on the Limit State approach are required to consider the type of the GRSSs, the surroundings and size of the structure, the type of existing ground conditions and the position of the water tables and the nature of the operational environment.

Of particular importance in the Limit State approach to the design of GRSSs are the considerations given to “strain compatibility” of the constituent materials at the various limiting conditions and the assessment of the significance of the internal and external environmental conditions on the durability of the composite materials.

The Hybrid (Transitional) Approach

Hybrid (Transitional) approaches seek to represent the soils at their Ultimate Limit States by their Peak Angle of Friction [ϕ'_p] and the geosynthetics by factored long-term creep rupture strength. All loads are treated as equivalent sustained loads acting over the whole design life. Short-term loads, e.g. accidental or seismic loads, are checked to ensure that their sum is equal or less than the factored short-term strength of the reinforcement. Partial Factors are applied to the properties of the soils and the geosynthetics. Global Factors of Safety are applied within the internal and external stability analysis. No strain compatibility is considered for the Serviceability Limit States. Likewise, within the Ultimate Limit State analysis the soils are represented by a factored Peak Angle of Friction [ϕ'_p]. Often the outcome designs are very similar to those obtained from Limit Equilibrium methods, Khan (1999) and McGown (2000).

The Recommended Approach

It is recommended that the “true” Limit State approach to the design of GRSSs should be employed, McGown et al (1994). With this approach, calculation of deformations / strains within the structure can be made and introduced as important design criteria. Thus both Ultimate Limit States [ULS], (i.e. collapse conditions), and Serviceability Limit States [SLS] can be considered. Furthermore, risk factors, so-called Partial Factors, can be introduced to replace the use of global Factors of Safety as used in Limit Equilibrium approaches. Some of the latest national and international design codes / methods employed in the design of GRSSs are seeking to implement the Limit State approach and hopefully, all of the possible improvements and economies to be derived from employing the Limit State approach may be achieved, always providing realistic / appropriate choices are made for the design input parameters.

WHAT DEFINES A STEEP SLOPE AND A WALL?

For unreinforced steep slopes and walls the likely mechanisms of failure, the choice of design input parameters and the choice of Factors of Safety have been historically kept separate and linked to different well established analytical techniques developed by various individuals, including Coulomb, Rankine, Culmann, Bishop, Morgernstern, Janbu and Skempton. However, the change from steep slope to wall was rarely if ever defined, rather it was presumed that the decision to construct a steep slope or a wall would be taken for various non-analytical reasons, such as the amount of land available or aesthetics. Further, without internal reinforcement, there were difficulties with the construction of very steep slopes and so the decision to construct a wall or not, was often fairly clear.

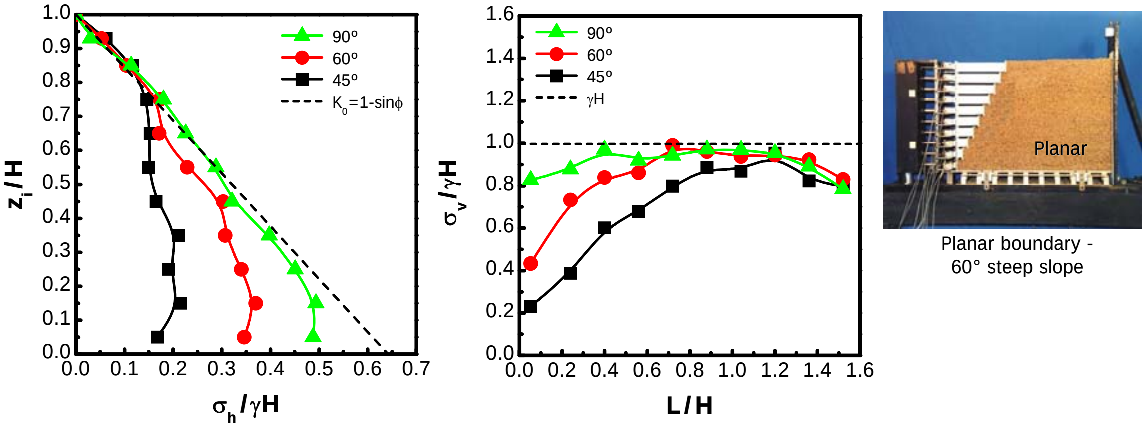
For geosynthetic reinforced steep slopes and walls, the possible mechanisms of failure and the design input parameters are greater in number than for unreinforced structures. However, the distinction between reinforced steep slopes and walls is much less by virtue of the use of internal reinforcements in both cases. Further, the construction of geosynthetic reinforced steep slopes with high angle lateral boundaries, is very similar to that of internally reinforced walls. Nevertheless, to date the application of different global Factors of Safety, Material Safety Factors and / or Partial Factors is common practice. The reason for this appears to be a straight carry over from the analysis of unreinforced soil structures.

For the Limit Equilibrium and Hybrid (Transitional) approaches it is, by virtue of their semi-empirical natures, best to retain the separate analysis of internally reinforced steep slopes and walls. For “true” Limit State analysis the choice of Partial Factors is based on clearly defined analysis of risk. Therefore it is suggested that it is justified in the “true” Limit State approach to integrate the analysis of internally reinforced steep slopes and walls, albeit the choice of Partial Factors must be carefully made and be linked to the shape and nature of the lateral boundary and the imposed actions.

WHAT ARE THE BENEFITS OF NON-LINEAR LATERAL BOUNDARIES?

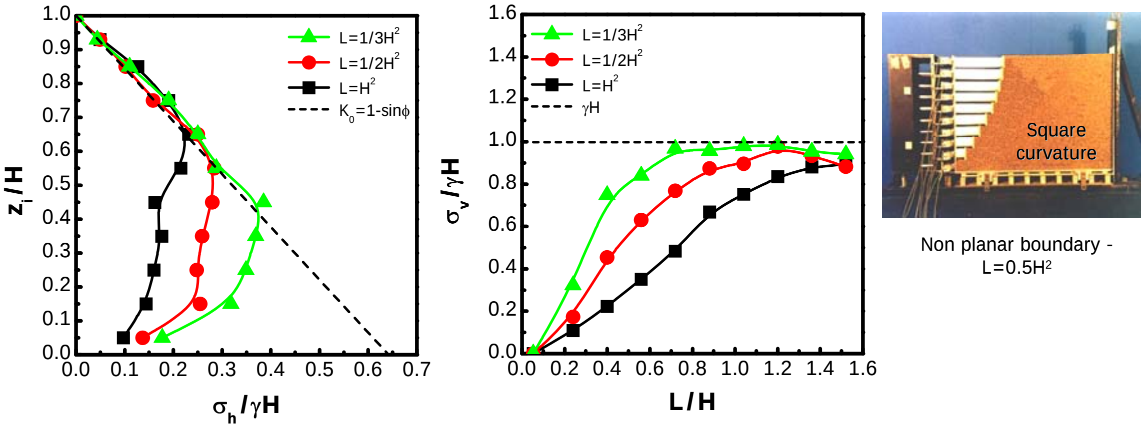
Non-linear (variable angle) lateral boundaries may take many forms, as shown in Fig. 1.

The influence of the shape of the lateral soil-wall boundary has been identified on the basis of small-scale laboratory testing by Kupec (2004). The tests were conducted on a brass rod model with rigid lateral planar and non-planar boundaries and demonstrated that the greatest benefits were obtained from the use of particular forms of variable angle lateral boundaries, such as square or cubic functions. These were associated with the curved lateral boundaries as shown in Fig 1b and 1c. The main benefits were deemed to be two-fold, i.e. the possibility of more uniform lateral earth pressures over the height of the structure and reduced toe bearing pressures.



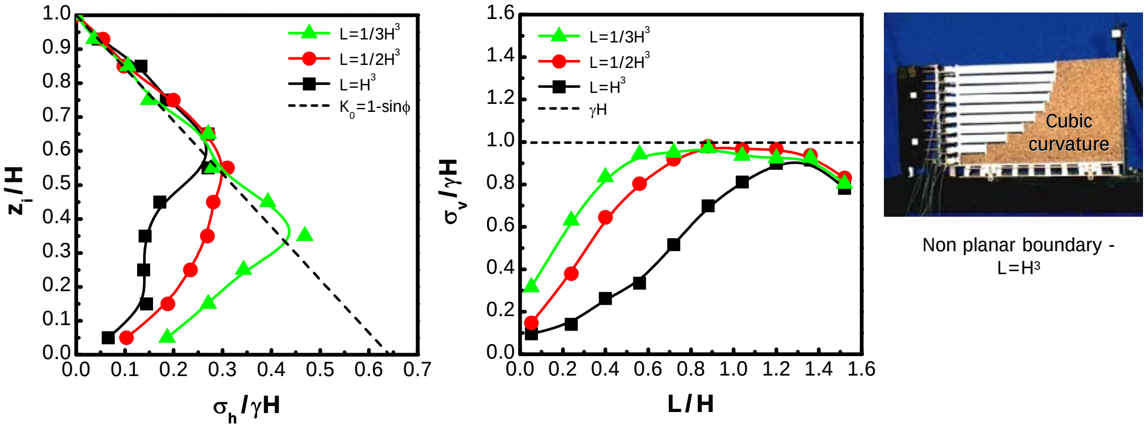
(a) Lateral pressures (b) Basal pressures

Figure 1a Planar conventional soil wall boundaries



(a) Lateral pressures (b) Basal pressures

Figure 1b Non planar – square lateral soil wall boundaries



(a) Lateral pressures (b) Basal pressures

Figure 1c Non planar – cubic lateral soil wall boundaries

Figure 1 Variation in form and shape of the soil-wall boundary for walls and steep slopes at different boundary conditions, after Kupec (2004)

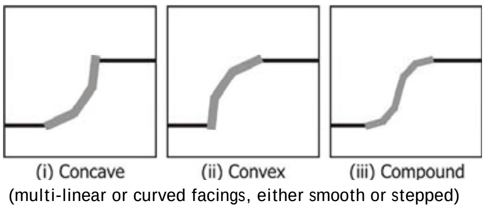
To date increasing lateral earth pressures with depth and large toe bearing pressures associated with planar lateral soil-wall boundary conditions, have greatly limited the application of GRSSs in practice. The possibility of controlling these factors by adopting non-planar lateral soil-wall boundaries appears to have considerable potential.

The method of constructing GRSSs is to place successive layers of compacted fill and reinforcement, with the latter connected to facing units or formed into a wrap-around facing. For construction simplicity it is desirable to keep the thickness of the compacted fill layers the same and employ only one or two types / grades of reinforcement over the height of the structure. To do this, the pressures to be resisted at the lateral boundary require to be as uniform as possible. This will have the effect that the loads carried by the various layers of geogrid reinforcement are very similar over the full height of the structure. As a direct result, the lateral boundary (or facing) deformations will be very uniform and the required geosynthetic reinforcement stiffness very similar.

By standardising the types, layout and lengths of the reinforcements, there are considerable economic benefits to be gained. Another benefit is achieved by keeping the spacings between individual layers constant, using constant anchorage lengths and employing only one or two reinforcement types / grades within the structure. Furthermore, end users and designers have the possibility to specify or create GRSSs with non-planar (variable angle) lateral boundaries that may have many aesthetic advantages over conventional structures and as a result be less intrusive, especially if vegetated facings are used.

HOW SHOULD NON-LINEAR BOUNDARIES BE DESIGNED?

For the Limit Equilibrium and Hybrid (Transitional) approaches to design it is suggested that for those parts of the structures with lateral boundaries less than 70º they be treated conventionally as reinforced steep slopes and for those parts of the structures with lateral boundaries more than 70º they be treated conventionally as walls. However, great care should be taken to fully analyse the overall stability of the structure and to consider in detail the conditions at the interface between the parts considered as a wall and a steep slope. In some cases this may involve a steep slope overlying a wall and in other cases the reverse, Fig. 2.



- The underlying philosophy is that the soil-wall boundary is shaped to control earth pressure levels and distributions
- Only sectional facings with reinforcements allow this to be developed

NOTE: Either smooth facings or stepped construction can be used.

Figure 2 Possible variations of the soil-wall boundary

For the "true" Limit State approach there should be no need to split the structure into parts. All possible failure and deformation mechanisms, both internal and external, can be considered in order to test whether the structure will fail or deform in a mode similar to a conventional reinforced soil steep slope or wall. Undoubtedly FEM and other numerical methods will be very useful in such analysis. Thus, it is suggested that structures with non-linear (variable angle) lateral boundaries may be analysed in a coherent and integrated manner.

WHICH FACTORS OF SAFETY, MATERIAL SAFETY FACTORS AND / OR PARTIAL FACTORS ARE APPROPRIATE?

As stated previously, in the Limit Equilibrium and Hybrid (Transitional) approaches, the choice of global Factors of Safety, Material Safety Factors and / or Partial factors are generally directly associated with the particular method of analysis employed and should not therefore be modified without very careful consideration.

For the "true" Limit State approach the choice of Partial Factors is dependent on well defined risk factors and these may be varied according to the specific conditions related to the structure under consideration. Thus providing careful consideration is given to their choice, different sets of Partial Factors need not be assigned to different parts of the structure.

DISCUSSION

McGown (2000) estimated that by employing the "true" Limit State approach applied to the design of GRSSs the costs associated with design, construction and materials may be greatly reduced. By including the benefits that may be achieved by optimising the shape of the lateral boundary and standardising the design and construction of GRSSs, it is suggested that the project costs may be reduced even further.

To date, the use of Computer Aided Design [CAD] programs for the design of GRSSs is common practice and numerous software packages for conventional and reinforced earth structures are readily available. The changes to current design programs to include non-linear (variable angle) lateral boundaries, as discussed in the above sections, are deemed to be minor. The underlying design philosophy suggested is to determine the maximum long-term strength that can be resisted by the geosynthetic reinforcement, to adopt appropriate Partial Factors and then change the shape of the lateral boundary to ensure that the maximum allowable strength is not exceeded in any part of the structure.

Thus it appears that by utilising a coherent, integrated design approach to geosynthetic reinforced steep slopes and walls, with or without non-linear (variable angle) lateral boundaries, end users and designers will have the opportunity to gain further cost and aesthetic benefits without loss of operational performance.

By adopting the "true" Limit State approach, it is suggested that there is no need for separate types of analysis for those structures with linear lateral boundaries that have to date been designated as steep slopes or as walls. Additionally, for geosynthetic reinforced soil retaining structures with non-linear (variable angle) lateral boundaries a coherent, integrated "true" Limit State design approach is also appropriate.

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