AN ASSESSMENT OF THE USE OF GEOGRIDS IN EARTH RETAINING STRUCTURES

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INTRODUCTION

Many years before the introduction of geogrids as a soil reinforcement, the relevant Civil Engineering Code of Practice in United Kingdom defined Earth Retaining Structures as, "… *any type of structure required to retain soils at a slope steeper than that which they would naturally assume, or to protect soil banks against destructive agencies*". Further, it suggested that the design of such structures included, " … *all things needful to make it fulfil its purpose, i.e. to ensure that it be strong, durable, economical in first cost and maintenance and pleasing in appearance*", Institution of Structural Engineers (1951). In this single Code of Practice all the available types of gravity, reinforced concrete, steel and timber soil retaining structures, cribwork and revetments were included and the design criteria given in this code remain applicable.

In the late 1960's, *Terra Armee,* (Reinforced Earth), was developed, Schlosser and Vidal (1969). It was generally applied to the construction of retaining walls and very steep slopes and involved the reinforcement of well compacted granular soils with metal strips. In the early 1970's, polymeric strips and straps, (some formed into grids), geotextiles, geonets and geomeshes were introduced as reinforcements in retaining walls, steep slopes and embankment side slopes. In the early 1980's, geogrids with integral junctions were added to the range of geosynthetics used as soil reinforcements, but by that time, reinforced soil retaining walls and very steep slopes, (>70^o), were, for mainly regulatory reasons, separately designed and assessed, DTp. (1978). This separate consideration of reinforced soil retaining structures from other forms of Earth Retaining Structures and the split between reinforced soil walls / very steep slopes and other reinforced slopes including embankment side slopes, has persisted to the present day.

Although geogrid reinforced soil retaining structures are now dealt with in design codes and standards, the approach taken to their design and performance assessment has remained essentially the same as that initially introduced for *Terra Armee,* which assumes the development of the Ka stress state in the reinforced soil. However, from the early 1980's onwards a great deal of research has been undertaken on the properties of the various types of geogrid reinforcements. In contrast, much less research has been undertaken on the properties of the soil fill being reinforced and on the composite behaviour of the soil and reinforcement. Therefore at this time there are some aspects of geogrid reinforced soil retaining structures which have been well researched and for which little further research is needed, whilst there are other aspects which require further research and development in order to gain the full technical, cost and environmental benefits from their use.

In this paper, the various forms of geogrid reinforced soil walls and slopes are identified and their components are described. The nature of the loads to be supported and the critical deformations developed are then identified. Following this the current level of knowledge of the behaviour of each structural component and of the overall structure is assessed and areas of possible future research related to these are suggested. Present and future design approaches are discussed and the need for more appropriate numerical models is presented. The important role of construction methods is emphasised and the need to develop innovative techniques is identified. Finally the technical, cost and environmental benefits of the use of geogrid reinforced soil structures are considered and the possibility of gaining a better understanding of these is suggested.

STRUCTURAL FORMS, COMPONENTS AND FUNCTIONS

Forms

The lateral boundary of a geogrid reinforced soil structures is normally formed by one or more linear, or stepped, sections which have slope angles as high as 90^0, (vertical), or as low as 30^0, (approximately the constant volume angle of friction of the soil to be reinforced). Depending on the slope angle of the lateral boundary, it may be described as a wall, steep slope (battered wall), slope or embankment side slope. In some situations a combination of a wall and a slope is used to form the lateral boundary of the structure.

The main technical reasons given for splitting the various forms of reinforced soil retaining structures into walls / very steep slopes and other slopes, including embankment side slopes, are the need for facing units and the greater requirements for a stable sub-soil for walls and very steep slopes, Bonaparte et al (1985), BS8006 (1995), Jewell (1996) and Floss (2004). However, this split is particularly questionable for geogrid reinforced soil structures as there are other factors which can be critical to the design and performance of different forms of these structures. Hence it is suggested that it is appropriate to treat all forms of geogrid reinforced soil retaining structures as a single group.

A particular example of a critical factor related to the performance of geogrid reinforced soil retaining structures is whether or not the particle size distribution of the soil to be reinforced and the aperture size of the geogrids are appropriately matched. If not well matched then the soil - geogrid interaction mechanism will rely mainly on surface friction rather than on soil interlock. Thus the geogrid reinforced soil will behave in a similar manner to *Terra Armee* and to other types of geosynthetic reinforced soil. If well matched to the soil, the geogrid will develop high degrees of soil interlock and this can produce a truly "*composite material*". In fact, geogrid reinforced soil structures which have a high degree of soil interlock can behave in a similar manner to the gravity wall / slope structures dealt with in the Code of Practice for Earth Retaining Structures, Institution of Structural Engineers (1951). Additionally, Kupec et al (2008) have suggested that non-linear, variable angle lateral boundaries for Earth Retaining Structures have many technical advantages and geogrid reinforced soils which have a high degree of soil interlock are particularly suitable for use in such structures.

Components

The components of geogrid reinforced soil retaining structures may contain some or all of the following components:

Facing Units
Connections
Wall Foundations
Geogrid Reinforcements
Reinforced Soil
Retained Fill
In-situ Soil
Sub-soil

Functions

The basic functions of geogrid reinforced soil retaining structures are to allow on a temporary or permanent basis, a change in ground level, protection of an existing natural slope and / or resistance to external loading. To perform these functions, they are required to resist a wide range of loads and imposed deformations which may vary with time. As result they may be subject to various forms of settlements and lateral movements, including:

Loads - construction equipment; compaction forces; self weight, traffic loading; loads from supported or adjacent structures; seismic loading; impact loading; ground water tables and flow; wave action.

Deformations - compaction, settlement or collapse of the sub-soil; settlement of the reinforced fill, retained fill or in-situ soil; vertical and lateral movement of facing units, connections and wall foundations; strains in the reinforcements.

FACTORS TO BE CONSIDERED IN DESIGNS AND PERFORMANCE ASSESSMENTS

The first step in any design / performance assessment of a geogrid reinforced soil retaining structure should be the specification / consideration of the construction process used to build the structure. All too often this step is overlooked and possibly the most critical loads and deformations to which the structure will be subject are not identified. Therefore, only after full consideration has been given to the construction stage, should the design or performance assessment of the "as-built" structure be undertaken.

The factors to be considered in designs and performance assessments of geosynthetic, including geogrid, reinforced soil retaining structures were previously identified by McGown et al., (1998). They suggested that these factors could be grouped into three categories, viz., Serviceability, "*Internal*" Ultimate and "*Overall*" Ultimate Limit State criteria.

The Serviceability Limit State criteria are related to allowable limits for:

i) Vertical and / or lateral deformations of the facing or lateral boundary surface,
ii) Settlement and creep strains within the reinforced fill,
iii) Settlement and creep strains within the sub-soil,
iv) Collapse of part of the sub-soil,
v) Deformations induced in supported or adjacent structures.

The Internal Ultimate Limit State criteria are related to the failure of the components of the reinforced soil, as follows:

i) The stability of the reinforced fill close to the lateral boundary,
ii) Rupture or pull-out of the connections
iii) Rupture or pull-out of the reinforcements
iv) The stability of the wall foundation.

The Overall Ultimate Limit State criteria are related to the overall stability of the structure, as follows:

i) Base sliding,
ii) Bearing capacity failure in the sub-soil,
iii) Lateral spreading of the sub-soil,
iv) Overturning of the reinforced soil block,
v) Global stability.

It should be noted that it is possible to develop combined Internal and Overall Limit States.

CURRENT LEVEL OF KNOWLEDGE AND RESEARCH NEEDS RELATED TO COMPONENTS

General

Only some aspects of the properties of the different components and their interaction are well understood, thus there are a number of areas of research and development that still require to be undertaken. The current level of knowledge and the research needs related to the components, are described in the following sections.

Facing Units, Connections and Wall Foundations

The factors controlling the choice of facing units include aesthetic appearance, protection from UV light, prevention of surface erosion, wave attack, vandalism, fire protection and environmental requirements such as the need for a "*green*" facing. As a result there are now many different types of facing and these are usually associated with particular types of connections to form so called "*facing systems*", Jones (1996).

The technical specification for the mechanical, durability and environmental properties of the facings systems are usually available from or are provided by the manufacturer or supplier of the geogrid. Often there are test results to show compliance of the facing systems with the requirements of existing standards and codes of practice. There are a number of technical papers published on the design, construction and testing of facing systems for geogrids of which Jas et al (2004) and Jenner et al (2004) are two recent examples.

Depending on the type of facing, a simple wall foundation or levelling pad may be required. Such foundations can sometimes be required to prevent erosion, scour or frost damage at the base of the facing. Once again, the technical specification for this component is usually provided by the manufacturer or supplier of the geogrid.

Geogrid Reinforcements

Geogrid reinforcements are manufactured from a wide range of polymers which may be extruded into bars, fibres, filaments that are drawn to alter their physical and mechanical properties. They are then formed into two or more sets of ribs which are connected at cross over points, (junctions), by entanglement, heat or chemical bonding or by welding. Alternatively they may be formed by drawing extruded punched sheets to produce geogrids with integral junctions.

The drawing processes change the molecular alignment of the polymers from amorphous to semi-crystalline and as a result the load-strain-time-temperature characteristics of the polymers are improved, but it should be noted that in any geogrid the alignment of the polymer is not necessarily uniform. Particularly at or near junctions, there may be gradually varying degrees of alignment from amorphous within the junctions to semi-crystalline at the end of the ribs. Thus in order to ascertain the operational properties of geogrid products it is always necessary to test representative samples of products rather than individual parts such as single ribs or junctions.

Until recently geogrids could be divided into two main groups, uniaxial and biaxial products, Fig. 1. However triaxial, (tri-directional) products are now being manufactured and used in practice, therefore there are now three separate types of geogrids.

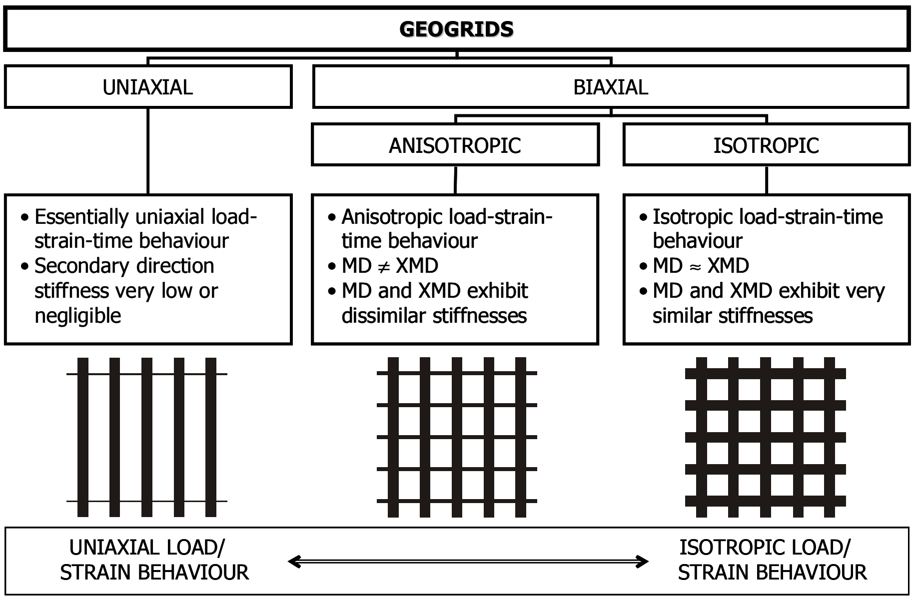

Figure 1: Various Types of Uniaxial and Biaxial Geogrids, (McGown and Kupec, 2008)

In order to assess the consistency of the properties of the geogrid products to be used in applications, "*Quality Assurance*" testing is required using standardised test methods, so-called "*Index*" tests, which are carried out on representative samples. Manufacturers may also carry out "*Quality Control*" tests on non-representative samples, including Index tests on single ribs or junctions. It is important to recognise the differences between these two types of Index tests. Further, in order to determine the operational performance characteristics of geogrids it is necessary to carry out operational "*Performance*" tests, Murray and McGown (1982). Only properties determined from

Performance tests should be used for design or performance assessment purposes. Some correlations between Index and Performance test data for geogrids have been proposed by various authors, but such correlations are at best product specific due to the different and complex molecular structures of the polymers forming the geogrid products.

Geogrids may be used as "*primary*" or "*secondary*" reinforcements in reinforced soil retaining structures. The role of the primary reinforcements is to provide both local and overall stability to the structure whereas the secondary reinforcements are required to provide only local stability at or near the facing, usually at points intermediate to the primary reinforcements, Fig.2.

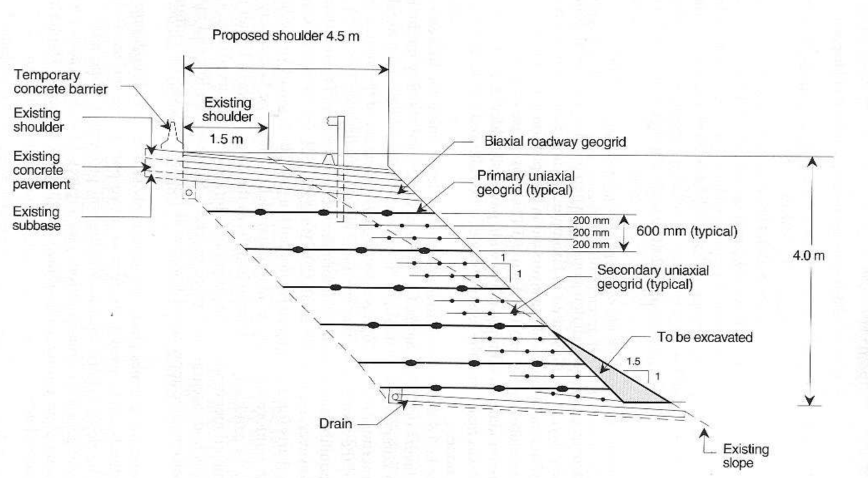

Figure 2: An Example of the Use of Primary and Secondary Geogrid Reinforcements, (Berg et al, 1990)

For both primary and secondary geogrid reinforcements, their operational load-strain-time-temperature behaviour and their ability to interact with the soil in which they are placed, are critical to their performance. Since their introduction, a considerable amount of research has been undertaken on developing test methods to determine the operational properties of geogrids. In this section only the research related to determining their load-strain-time-temperature properties will be discussed. Their soil interaction behaviour will be dealt with in a later section.

The operational load-strain-time properties of "as manufactured" geogrids are now undertaken on representative samples using standardised test methods, e.g. ISO / Dis 13431 (1999) and ASTM D5262 (2002). These are based on the research work on geogrids reported on by McGown et al (1985a and b) and are often carried out at different ambient temperatures ranging between 5 and 40 ^{o} C to assess the influence of temperature on the behaviour of the geogrids. These tests are all carried out "*in-air*", using sustained uniaxial tensile loads, Fig. 3, as confinement in-soil has not so far been shown to significantly influence the load-strain-time characteristics of geogrids.

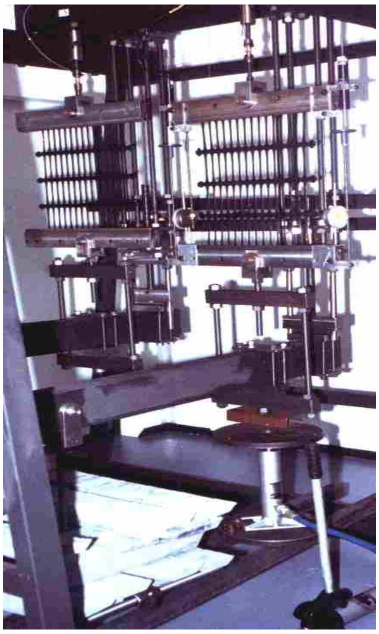

Figure 3: Sustained Loading (Creep) Testing of Geogrids

The application of the data obtained from tests on "*as manufactured*" geogrids, to the design of reinforced soil retaining structures is detailed in many Codes of Practice and Design Standards, such as BS 8006 (1995) and EBGEO (1997). Necessarily these codes and standards employ a range of Partial Factors to allow for various manufacturing, service, physical damage and environmental degradation effects. These Partial Factors are highly significant and can greatly reduce the serviceability and ultimate strengths used in designs or in back-analysis of structures. There are many approaches to determining these Partial Factors, with almost all related to the ultimate conditions, using both load or strain criteria, Voskamp (1989) and McGown (2000).

Reinforced Soil

When *Terra Armee* was introduced, the soil type to be reinforced was closely specified. It was defined as a well compacted, free draining, well graded granular soil**.** The restrictions on the level of compaction to be used, drainage properties and grading of the soil to be reinforced were, with notable exceptions, continued over to the early geosynthetic reinforced soil retaining structures, including the early geogrid reinforced structures. One consequence of this was that the aperture sizes in geogrids were to some extent selected to match the particle size distribution of the soil originally defined for use in *Terra Armee*. The relationship between the particle size distribution of the soil and the aperture size of the geogrid, was identified by Jewell (1980) and Jewell et al (1984). Thus in order to achieve a high degree of interlock between most geogrid reinforcement products and the soil in which they are embedded, designers require to specify a soil type close to the soil that was originally used for *Terra Armee*. Unfortunately the in-situ soils at or close to many sites where geogrid reinforced soil structures are to be used do not conform to the original *Terra Armee* specification. Thus the soil to be reinforced has either to be imported or a lower degree of interlock accepted in the design.

Very often, the importation of soil onto a site is not considered to be environmentally desirable / acceptable, hence the use of a much wider range of soil types, (natural soils or waste products), is of major importance. This may require either modification of the locally available soils or waste products, the use of geogrids with specifically matched aperture sizes and shapes and / or the provision of extensive drainage, Jones (1995).

Another aspect of the initial adoption of the *Terra Armee* design philosophy for geogrid reinforced soil structures was the use of the peak angle of friction, (or the constant volume angle of friction), to represent the behaviour of the soil. *Terra Armee* employed steel strips and these achieved their design strength at extremely low deformations / strains. Thus limit equilibrium design considerations were generally appropriate Geogrid reinforcements must strain significantly in order to develop their design strengths, hence either Serviceability or Ultimate Limit States may be critical to the performance of the structure. Additionally, it may be that the strain induced in the geogrids or the strain induced in the soil is the limiting factor. For this reason, knowledge of the relationship between the mobilised angle of friction and the strain in the soil is as important as knowledge of the load-strain behaviour of the geogrid reinforcement.

Soil Reinforcement Interaction

In most Codes of Practice or Design Standards, a critical factor is the determination of the pull-out resistance of the geogrid reinforcement from the soil in which it is embedded. This determines the length of the geogrid reinforcement layers, although in some cases there is a minimum length prescribed, e.g. BS8006 (1995). Based on the original work on geogrid interaction with granular soils by Jewell et al (1985), a considerable amount of testing has been undertaken using both shear box and pull-out box test apparatus, Figs. 4 and 5.

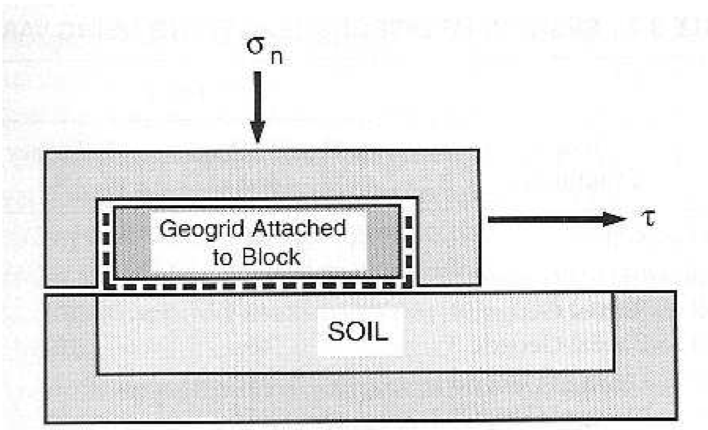

Fig. 4: Shear Box Apparatus for Testing Geogrids, (Koerner, 1999)

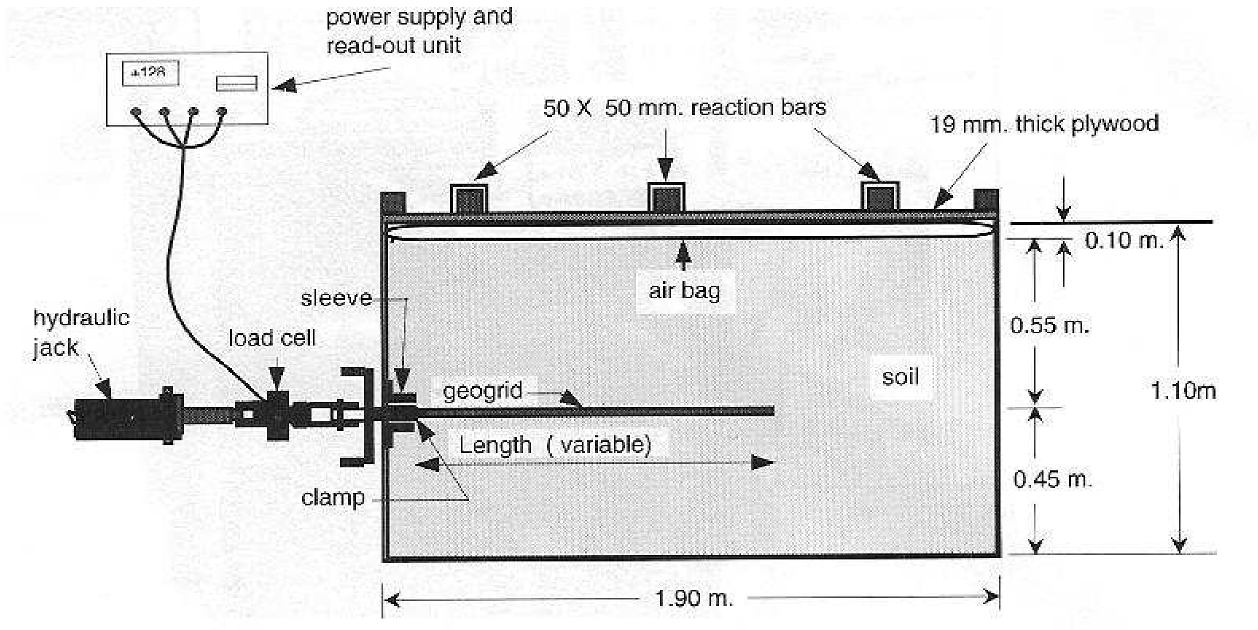

Figure 5: Pull-out Testing Apparatus for Geogrids, (Koerner, 1999)

To date such tests have not provided all the information required on other effects of the interaction between the geogrid and the soil, such as the local confining effect on the soil, the so-called "*Dynamic Interlock*" effect, McGown et al (1990). Additionally they have not identified the extent of the zone of influence of the geogrid on the soil in which they are embedded. Nevertheless, these factors can be very important to the design and performance assessment of geogrid reinforced soil retaining structures.

Retained Fill, In-situ-soil and Sub-soil

It is suggested that the present level of knowledge of the behaviour of the retained fills, in-situ-soils and sub-soils is well understood for the purposes of designing and assessing the performance of geogrid reinforced soil retaining structures.

CURRENT LEVEL OF KNOWLEDGE AND RESEARCH NEEDS RELATED TO THE OVERALL BEHAVIOUR OF STRUCTURES

The analysis of the overall stability of geogrid reinforced soil retaining structures is usually taken to be the same as for conventional Earth Retaining Structures and includes consideration of sliding, overturning, tilting / bearing and overall slip failures, Fig.6.

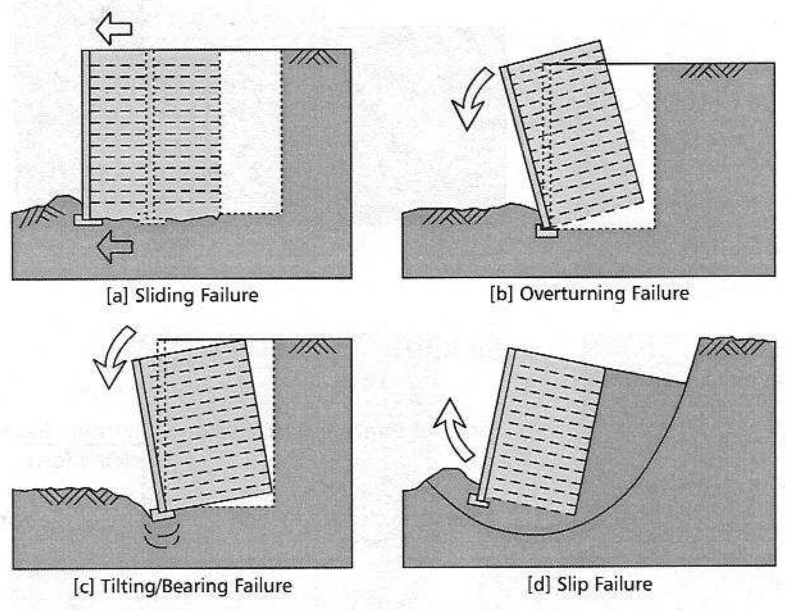

Figure 6: Assumed Overall Failure Mechanisms for Geogrid Reinforced Soil Retaining Structures

The basic assumption made is that the reinforced soil block behaves as a rigid body. The validity of this assumption depends on the amount of reinforcement used and the degree of interlock between the soil and the geogrid reinforcements. For lightly reinforced structures and for low degrees of interlock combined overall and internal slip surfaces may develop and the reinforced block may behave in a flexible rather than a rigid manner, with resulting changes in the base pressure distribution. These changes will influence the mechanisms of overturning and tilting / bearing failure. Additionally, Kupec et al (2008) have suggested that variable angle lateral boundaries can reduce the lateral boundary earth pressures and the maximum base pressure of the reinforced soil block. Thus the mechanisms of overturning and tilting / bearing failures would once again be modified and be less conservative than those normally assumed.

CURRENT LEVEL OF KNOWLEDGE AND RESEARCH NEEDS RELATED TO DESIGNS AND PERFORMANCE ASSESSMENTS

General

Since the introduction of geosynthetic reinforced soil retaining structures in the 1970's, design methods have gradually evolved, but the resulting outcome designs have not varied greatly. Indeed, it has been suggested that if anything, they have become more conservative, Berg et al (1998) and Greenway et al (1999). The reason for this is that as design method were developed, many were "*calibrated*" through the choice of values for the Global Factors of Safety and Partial Factors to be adopted. These were chosen to ensure that the outcome designs were similar to those from design methods previously employed.

In this section, the particular aspects of the design and performance assessments of geogrid reinforced soil retaining structures to be considered are the characterisation of the Actions to be resisted and the analytical methods to be used.

Actions

The operational behaviour of geogrid reinforced soil retaining structures is controlled by the Actions imposed on the structure. These Actions have been classified in Eurocode 7 (1995) as "*Direct Actions*", which are loads or forces applied to the structure, and "*Indirect Actions*", which are imposed or constrained deformations. In view of the range of Actions that can affect the operational behaviour of the structures, their design and performance can be difficult to model. Further it should be recognised that some types of Actions may vary considerably with time. Thus it has been suggested by McGown (2000) that Actions should be spilt into three general categories, viz. "*Sustained Actions*", "*Equivalent Sustained Actions*" and "*Sustained plus Short-term Actions*", Fig.7.

Sustained Actions and Equivalent Sustained Actions represent all types and combinations of Actions that can be reasonably represented as long term sustained loads or deformations and are termed "*Single Stage Actions*". Sustained plus Short-term Actions are those which must be treated in designs or performance assessments as a series of loads or deformations acting for different periods of time, either combined or separately, and are termed "*Multi-stage Actions*". McGown (2000) has considered the use of an Isochronous Strain Energy approach to represent the possible combinations of Actions in designs and performance assessments, but much more work is required on how this should be applied in practice.

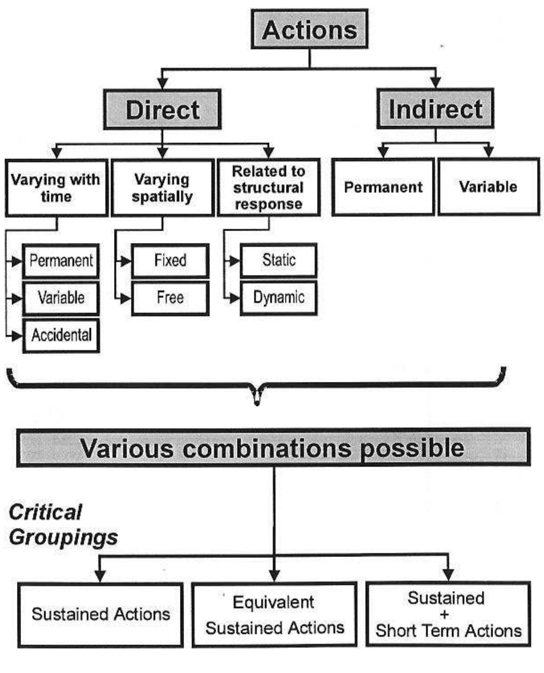

Figure 8: Classification and Grouping of Actions (McGown, 2000)

Analytical Methods

The first step in the development of design and performance assessment methods was the use of "*Empirical*" methods. These were based on the design approach developed for *Terra Armee* but modified to take account of the experience gained from the early trial and monitored geosynthetic reinforced soil retaining structures. Next "*Limit*

Equilibrium" methods were introduced which were based on classical soil mechanics principles for Earth Retaining Structures with the addition of geosynthetic reinforcements treated as pseudo-steel reinforcements. In addition large Global Factors of Safety were used which had the effect of limiting deformations at operational conditions. In the early 1990's the "Limit State Approach" was introduced. However, rather than move completely away from Empirical and Limit Equilibrium design methods, many design codes and standards introduced a modified version of the Limit State Approach. This modification involved the introduction of both Partial Factors and Global Factors of Safety to ensure that the outcome designs were much the same as for previously employed design methods. Such modified methods may be termed "*Hybrid*" design methods. As a result of this continuing process of "*calibration*" of the various methods using Global and Partial Factors, the vast majority of outcome designs have remained very conservative and very few failures have been reported, Giroud (1999).

In order to progress the design of geogrid reinforced soil retaining structures there should be a move away from the Hybrid design approach to a "true" Limit State Approach. Within these new design methods, much more emphasis should be placed on the determination of deformations at working and serviceability conditions. Additionally they should not involve the use of any Global Factors of Safety and should involve the use of much less conservative Partial Factors. An approach worthy of consideration is the use of a much greater range of values for the Partial Factors. They should be closely linked to risk, with simple low risk structures having the absolute minimum possible values of Partial Factors applied in the design and more complex, high risk structures having much higher values applied. In this way, economies may be obtained for the vast majority of geogrid reinforced soil retaining structures which are essentially low risk structures, and yet complex structures in high risk situations may still be designed conservatively.

With the development of computing capacity, numerical modelling / analysis has been advancing, particularly for performance assessments. Within these, the numerical models used to represent the behaviour of the various components are gradually becoming more appropriate. Additionally the modelling of construction processes is becoming more common. A key issue will be the choice of input data to represent the soils, the geogrid reinforcement, soil geogrid interaction and the properties of the other components. The suggestions made in previous sections, with regard to the testing and representation of the various components of geogrid reinforced soil retaining structures in designs, are critical to the development of new numerical modelling techniques.

CURRENT LEVEL OF KNOWLEDGE AND RESEARCH NEEDS RELATED TO CONSTRUCTION TECHNIQUES

Several aspects of the construction process employed to form geogrid reinforced soil retaining structures are known to be critical to their operational performance and should be specified. These include:

(i) Placing and supporting the facing system
(ii) Storing, handling and laying the geogrid reinforcement
(iii) Storing, laying and compacting the soil to be reinforced
(iv) Connecting the facing system to the geogrid reinforcement.

A great deal of research, testing and monitoring of full-scale structures has been undertaken to establish the influence of the construction procedures on the various types of facing systems and their connection to the geogrid reinforcement, Jones (1996). It has been shown that the procedures adopted during the construction stage may greatly influence the earth pressures at or near the facing and the distribution of loads along the geogrid reinforcement, McGown et al (1998), but further research and development work is still required.

Another important area of research has been focussed on the influence of construction techniques on the physical damage of the geogrid during the construction stage. However, much of this work has been directed towards the measurement of the effects at ultimate conditions rather than at serviceability conditions.

Since the introduction of geogrids, the basic construction process for walls, steep slopes, slopes and embankment side slopes has remained the same. It has involved laying out the geogrids in roll wide widths in the direction at right angles to the lateral boundary, In contrast, the soil and the facing are usually placed in the direction parallel to the lateral boundary. The reason for this is that the original construction procedure for *Terra Armee* is being followed. As a consequence, most geogrid reinforcements are manufactured to be stronger in their machine direction.

The adoption of the *Terra Armee* construction procedure generally avoids the need for jointing of the geogrids but slows down the construction process. However were the geogrids to be stronger in the cross-machine direction and laid out parallel to the facing, a more rapid construction process could be employed providing that the edges of the geogrids could be efficiently connected to the facing system and, if necessary, efficiently connected to another parallel roll of geogrid, thereby providing sufficient anchorage length / pull-out resistance. Little or no research has been carried out on the benefits to be gained from this change in the construction procedure.

CURRENT LEVEL OF KNOWLEDGE AND RESEARCH NEEDS RELATED TO THE DERIVED BENEFITS

Rarely are the technical benefits identified and set down in an ordered manner for any particular site application. Generally all the other possible forms of Earth Retaining Structures have not been designed in detail and so comparisons cannot be made. Whenever there is detailed information on alternatives structures, then identifying and reporting on the technical benefits to gained from the use of geogrid reinforced soil retaining structures, would be most useful,

Cost benefits have to date been one of the main justification for using geogrid reinforced soil retaining structures. Commercial confidentiality has often prevented detailed reporting of the relative costs of alternative designs. Whenever there are fully detailed costs available, reporting on the cost benefits of using geogrid reinforced soil structures would be most useful.

In recent times the identification of the environmental benefits accruing from the use of geogrid reinforced soil structures has become a major issue / requirement, GEO (2002). Much more research and development work related to the quantification of the environmental benefits requires to be undertaken.

FUTURE RESEARCH NEEDS

- The present level of knowledge with respect to the design and performance of facing units, connections and wall foundations is adequate and that little further research is required in the near future. However, some development work and further testing may be required.
- The present level of knowledge with respect to the in air measurement of the uniaxial load-strain-time-temperature properties of uniaxial and biaxial geogrid products is sufficient. Thus little further research is required in this area in the near future, although improved dissemination of the research results is required. Further research is, however, required on the behaviour of biaxial geogrids under biaxial loading conditions and on the behaviour of the newly introduced, triaxial geogrids under uniaxial, biaxial and triaxial loading conditions. For all types of geogrids, it is suggested that further research is required on the quantification of Partial Factors, with particular emphasis placed on evaluating the influence of physical damage and chemical degradation at different operational strain ranges, rather than just at ultimate conditions. Additionally, the application of Strain Energy concepts to the interpretation of biaxial and triaxial geogrid behaviour and to the effects of physical damage and chemical degradation, is considered to be an area of future research.
- A considerable amount of further research is required on the use of a much wider range of natural soils and waste products in geogrid reinforced soil retaining structures. This may involve the development of innovative soil improvement and compaction techniques, the modification of the structure of some geogrids or the use of specialist drainage techniques. With regard to all soil types or waste products, it is suggested that future research should focus on the determination and characterisation of the relationship between their mobilised angle of friction and strain and on means of draining fills with poor drainage characteristics.
- The measurement of the pull-out resistance of geogrids is well established and little further basic research is required in this area. However, further testing will require to be undertaken on new types of geogrids in standard soils and on both existing and new types of geogrids in non-standard soils. Future research should be directed towards identifying for geogrids embedded in different soil types, the local confining effects of geogrids, the extent of the zone of influence of geogrids and the global properties of the composite material.
- No further research is required in this area although more emphasis on the influence of soil settlements and creep strains on the behaviour of geogrid reinforced soil structures is required.
- The present approach to the overall assessment of structures is most often is based on the assumption that the reinforced soil block is rigid. Future research should be directed towards investigating the problems and benefits arising from the assumption of the rigidity of the overall structure and the shape of the lateral boundary.
- The classification of Actions is well understood, however, there is much more research required in order that the various categories of actions may be appropriately applied in designs and performance assessments of geogrid reinforced soil retaining structures.
- Considerably more research and development work should be undertaken in order to allow the introduction of a “true” Limit State design method. These should not be “calibrated” to maintain the same outcomes as previously used design methods. Further, much more research and development work should be undertaken to develop more appropriate numerical modelling techniques for performance assessments.
- More research and development work should be undertaken on all aspects of the influence of the construction techniques on the performance of geogrid reinforced soil retaining structures.
- More research and development work related to the identification and quantification of the technical and cost benefits needs to be undertaken. Particular emphasis needs to be placed on quantifying the environmental benefits to be gained from the use of geogrid reinforced soil retaining structures.

CLOSING REMARKS

This paper represents a highly personal assessment of the use of geogrids in Earth Retaining Structures and is intended to provoke discussion, rather than to set out a structured view on the way forward. Hopefully following on from the discussion of the views expressed, the need for future research and development work will be identified and priorities agreed.

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