SIGNIFICANT DEVELOPMENTS OVER THE LAST 25 YEARS

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INTRODUCTION

In the last 25+ years there has been an enormous expansion in the use of geosynthetics in general and geogrids in particular. It is now very difficult to find a construction site that does not have any geosynthetics in some form or other performing one of the standard functions of separation, filtration, reinforcement or acting as a barrier. The reason for this high degree of acceptance is that there have been significant steps forward in the formalising of design methods and codes, where they can be applied and also very impressive practical success in the more empirical applications. This paper highlights the significant developments in the geogrid industry over the last 25+ years.

PRE 1984 SYMPOSIUM

Some polymer straps and strips were formed into grid-like products during the 1970's but the first integral geogrids were developed in the late 1970s and first employed in various applications in the early 1980's. These were the result of innovative research and development work carried out by Dr Brian Mercer following on from the extruded net technology that he had previously invented. These punched and stretched *Tensar* geogrids with their integral junctions were the forerunners of the many geogrid products we now see employed worldwide.

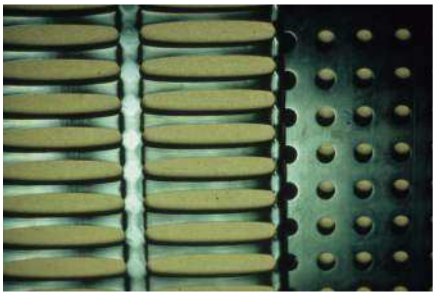

Figure 1. Punched sheet and uniaxial geogrid

Figure 2. Biaxial geogrid

SERC, now EPSRC, supported a large body of research work that culminated in presentations at the first geogrid symposium in (1984). The Universities of Leeds, Nottingham, Oxford, Sheffield and Strathclyde were all heavily involved in a comprehensive programme of research which examined the polymer technology, the development of innovative test methods to characterise the new materials and their application in walls, slopes, pavements, asphalt and concrete. In addition to the Universities a number of consultancy firms were also heavily involved, particularly Binnie and Partners through Nick Paine and Richard Jewell and Woodward Clyde Consultants through J P Giroud.

The team at West Yorkshire Metropolitan County Council, led by Professor Colin Jones, also formed an important part of the Soil Reinforcement Research Group by providing designs and construction details for actual construction to prove the materials and the structural applications.

There were no test methods for these new materials and the work by Professor McGown and the research teams at Leeds, Ward et al (1984) and Strathclyde, McGown et al (1984), teams concentrated on developing a testing regime for these new materials. It is interesting that we now have a very similar situation with the new geogrid materials with different shaped apertures which do not easily fit into the established testing regimes.

The University of Oxford, Milligan et al (1984), concentrated on the effect of geogrids in unpaved roads and on the soil / geogrid interaction mechanism producing illustrations that have been used in many presentations over the last 25 years.

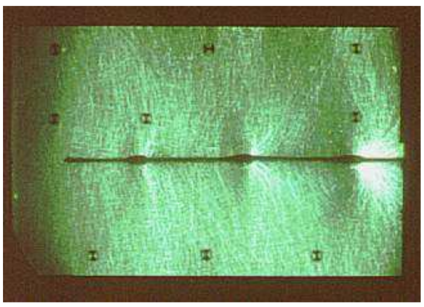

Figure 3. Pull-out of polymer geogrid

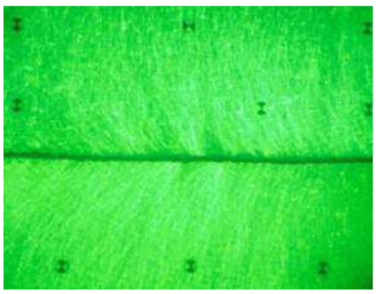

Figure 4. Pull-out of geotextile

Work on unpaved roads was also being carried out in N America with theoretical, laboratory and field projects. Carroll et al (1987). Design methods, Giroud et al (1984) which were an extension of those used for geotextiles, Giroud & Noiray, (1981) were developed and empirically based design was undertaken.

The University of Nottingham, Brown et al (1984), and The University of Waterloo, Haas (1984) worked on the use of polymer geogrids in the asphalt layers of pavements to extend life or even reduce the required asphalt thickness. This comprehensive research programme examined the benefits that could be gained in the problems of reflective cracking, fatigue cracking and rutting, with some very good results.

The University of Sheffield, Swamy et al (1984), Hobbs et al (1984) carried out some very interesting work on the possible applications of polymer geogrids in concrete. The ability of the polymer geogrids to absorb explosive or very rapid loads showed very good promise with finer crack patterns and more resilient behaviour of the concrete than conventional steel reinforced concrete, although any thoughts of longer term loading situations in structural reinforced concrete were dispelled. The use of polymer geogrids as the carrier for spray concrete in concrete repair situations evolved from this work and developed into a small but specialised market.

1984 SYMPOSIUM

The large body of research on geogrid testing and applications carried out during the early '80s was disseminated to a wider audience at the 1984 Symposium. The proceedings from this event also show that development in applications for geogrids in both structures and pavements was being carried out in parallel in North America.

The publication of this work was the real starting point for the geogrid industry we see today and many of the delegates and authors from the 1984 Symposium are either speaking or in the audience at this event confirming their long term commitment to the industry.

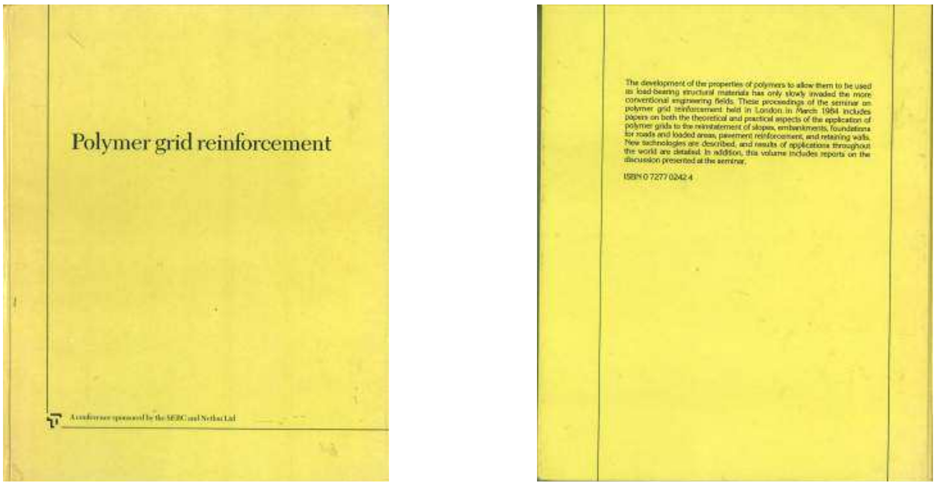

Figure 5. Symposium Proceedings

ACCEPTANCE

Structures

The next major step for the geogrid industry was acceptance by the Highway Authorities for the construction of geogrid reinforced soil walls and bridge abutments. This major step to include proprietary geogrid materials in the UK Highways Agency Advice Note BE 3/78, UK Department of Transport, (1978) in 1987, alongside the steel strip reinforcement that was the standard at the time, opened up many opportunities in infrastructure. The method of assessment of long term strength of polymer reinforcement was included in Appendix 1 of BE3/78 (1987) with the proviso that any non-metallic reinforcement required a British Board of Agrément Certificate before it could be used on a UK Highways scheme. It is interesting to note that the advent of polymer reinforcement also opened up the possibility of using pulverised fuel ash (pfa) as a fill material. This could not be used with steel strip soil reinforcement because of the chemical degradation of the steel by the very high pH material but a number of polymers remain unaffected by such extreme chemical properties.

This paved the way for a number of panel faced geogrid reinforced soil walls and bridge abutments to be designed and constructed in accordance with BE3/78, although the structures performed well, there was still a large amount of conservatism to be overcome in moving away from the conventional retaining structures formed in reinforced concrete, mass concrete, sheet piling etc. The bridge abutments supporting the highway over an underpass at Stirling in Central Scotland, were designed in accordance with BE3/78 using HDPE geogrids and pfa fill, Fig. 6. Snowdon et al, (1988).

As stated previously, there had been a number of grid-like products available in the 1970's but it was the concept of the aggregate interlocking within the geogrid apertures formed by stable integral junctions that was the significant development**.**

Figure 6. Stirling Bridge Abutments

Soil stabilisation and roads

Initially, the interlocking concept was most readily accepted in the applications of unpaved and paved roads where the effect of the geogrid was perceived to act in a more reactive role taking the impulsive loads that were transmitted from the vehicle wheels through the aggregate. Whilst there were already well established design methods for the structural applications, albeit for steel reinforcement elements, there were no design methods available for unpaved roads. J P Giroud pioneered the design methods that are still used today by developing theories that matched the performance of unreinforced unpaved roads and then extended those theories on an analytical basis to include the effects of, first geotextiles and then geogrids. Hence the design approaches that have been used until quite recently were evolved from an empirical base. Road design, even now, has a partial empirical element to it within the unreinforced pavement standards that have been developed in the UK and US.

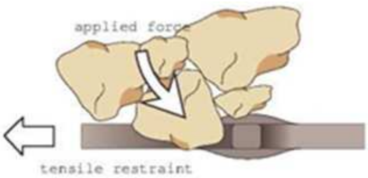

Figure 7. Interlock

A large amount of research into the performance of geogrids in unpaved roads has been carried out at the US Waterways Experimental Station, Webster (1992), University of Alaska, Kinney et al (1995), TRL in the UK, Watts et al (2004), KOAC in The Netherlands, Van Niekerk et al (2002), University of Illinois in the USA, Kwon et al (2006), and whilst all this work confirms that geogrid strength is not a critical factor it has not yet identified the fundamental mechanisms at work. However, it was certainly in the applications of geogrids to stabilise granular subbase layers that the greatest amount of material was used and construction of unpaved roads over soft soils using geogrids became a regular solution. The lack of defined parameters that can be identified and included in a design method has meant that the use of geogrids in permanent paved roads has been minimal although the benefits to be gained in that application could be significant.

Figure 8. Parking Area

Figure 9. Wind Farm Access

Research into asphalt reinforcement has also showed performance benefits, Brown et al (1985) and Haas (1984) but again a lack of understanding of the fundamental mechanisms has been a barrier to the inclusion of geogrids into standard design procedures for asphalt pavements. Whilst the use of geosynthetics in general in asphalt pavements is increasing the reasons are based more on performance than a true analytical understanding.

GEOGRIDS

During the 1980s a number of other types of geogrids became availble in the market place. Their development expanded the market considerably and also introduced many different ways of producing grid-like geosynthetic materials to be used in geotechnical applications. Fig. 10. Methods of manufacture ranged through welded, woven, knitted, extruded materials of varying tensile strength and base polymer. A number of these materials were adopted for both the structural and the stabilisation application areas using polymers that could provide long term strength under load as well as having the biaxial form which is more usual for the stabilisation applications. Figure 10.

Whilst the vertical and near vertical faced structures could now be designed to an authoritative document this was not thesame for steep slopes below 70^o and unpaved and paved roads. A number of proposed design methods were developed for steep slopes, Jewell et al, (1984), Greenwood, (1985), etc. based on two-part wedge analyses using limit equilibrium approaches. These methods also enabled the use of less competent fills than those conventionally used for vertical wall structures.

Figure 10. Geogrid variations

APPROVALS

During the later 1980s and the early 1990s there was considerable acceleration in the use of independent certification of products for structures in many countries. An important feature of certification was a link to a design method. Some authorities actually defined the method of design in the certification whilst others related the design values in the certification to existing national or governmental standards.

Hong Kong has a history of producing national design documents through the Geotechnical Control Office (GCO), now Geotechnical Engineering Office (GEO) to cover the particular soil and topographical conditions that prevail there. GCO certification of geosynthetic products for use in Hong Kong began in 1989, GCO (1989), with the certification initially linked to the BBA, in that certification only remained valid if there was a supporting valid BBA Certificate, BBA (1986). The basis for design was linked to the methods already specified in Hong Kong for standard geotechnical procedures for slope and retaining wall design.

The Institut Für Bautechnik in Germany also provided an independent certification process at around the same time which gave approval for materials to be used in nationally funded projects. The German Institut fur Bautechnik went one step further by including a specific design method within the certification documents themselves. DIBt (1988)

It is important to note that factors applied to the soil reinforcement materials and the particular soil properties differed in each of these certification mechanisms and hence it was not possible to use factors from one in another. Whilst this momentum of independent approval processes gave significant credibility to the technology it inevitably caused some confusion in the factors to be applied.

BRITISH STANDARD BS8006 (1995)

As early as the mid 1980s it was realised that an authoritative document which could provide guidance on the design of the large number of different reinforced soil applications would be a great benefit to the technology. The Department of Transport instigated the formation of a BSI committee to produce a Code of Practice that would cover all the current reinforced soil and soil nailing applications and design methods. The first members gathered at BSI in 1984 and it was to take over 10 years and many changes of membership before the Code was finally published. Fig. 11. BS8006 (1995).

The first steps taken were to commission a survey of existing practice and then to identify the good practice elements in order to determine what a code of practice should include. Once these reports were complete the committee divided into sub-committees to produce draft documents based on the large volume of information.

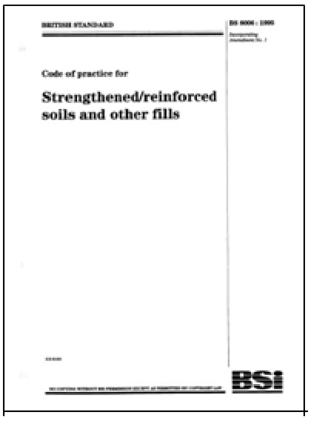

Figure 11. BS8006 (1995)

There was a large amount of discussion and disagreement and a calibration exercise was carried out by a small group to try to break through the differences in opinion produce a compromise which could be adopted by all. The collaboration between competitors and a willingness to work together to produce the details of the calibration exercise showed how important this Code of Practice was to them. There was, of course, vigorous and heated debate but there was a united effort to make the process work and to produce a document that could be accepted and used by all for the benefit of the industry. That same collaboration exists today between the members of the committee revising and updating the document.

BS 8006, Code of practice for strengthened/reinforced soils and other fills, was the first Code of Practice in the world to cover all aspects of soil reinforcement, vertical walls, steep slopes, shallow slopes, embankment basal reinforcement, embankment foundations over piles and void spanning. Figure 11. BS 8006
This comprehensive document was used as the template for many other equivalent documents around the world and, whilst there was some criticism of certain aspects, it was generally acknowledged as a significant step forward for the industry in general. In fact the International Geosynthetics Society (IGS) members who participated on the committee were jointly given an IGS Award for the work at the 6th IGS International Conference in Atlanta in 1998. The members were T. Ingold, C Jenner, C Lawson and B Myles.

There is no doubt that the publication of BS 8006 in 1995 was a highly significant event which gave enormous credibility to the technology of reinforced soil extending the applications beyond just vertical walls and steep slopes.

An additional document which was published by the Highways Agency in the UK in 1994 was the Advice Note HA 68/94 (1994) Design Methods for the Reinforcement of Highway Slopes by Reinforced Soil and Soil Nailing Techniques. This Advice Note extended the Highways Agency commitment to reinforced soil and also initiated a series of BBA Certificates for geogrid reinforcement products which were more suited to steep slopes where a high strength connection detail to a formal facing was not a requirement.

SEISMIC PERFORMANCE

Reports of good performance of geogrid reinforced soil structures in the USA were available in the late 1980s but it was the performance of geogrid reinforced soil structures in the Great Hanshin (Kobe) earthquake in 1995, that really brought the subject to the fore. Tatsuoka et al (1995) The earthquake reached a level above 7.0 on the Richter Scale and caused enormous damage in the area. The performance of the geogrid reinforced walls and steep slopes was the subject of reports and conference papers with conclusions that little or no damage occurred to the geogrid reinforced soil structures while conventional mass and reinforced concrete structures suffered badly from the seismic motions.

Figure 12. Examples of seismic damage of conventional reinforced concrete walls

The brittle nature of conventional structures is demonstrated clearly in Fig. 12 whilst the performance of a geogrid reinforced soil structure shows a completely different result, with even the deformation of the ground in front of the wall having little effect on the structure, Fig. 13.

Figure 13. Unaffected geogrid reinforced soil structure

The recognition of the performance of polymer geogrid materials in these events prompted investigative work on the properties of polymers under rapid, but short term, loading conditions by McGown et al (2000) and Jones et al (2007). This work is widely reported and has led to the adoption of much higher design values for the short term loading than those which apply for static design. The ability of the polymer materials used for reinforced soil structures to provide ductility to a structure without loss of integrity is a great advantage in these applications.

ALTERNATIVE DESIGN METHODS

There has been a large body of opinion that design methods for geogrid reinforced soil structures are very conservative in the amount of reinforcement strength required by the standard methods. The reason for this opinion is that monitoring of structure deformation does not match with the levels of geogrid strain that would be required to generate the required tensile resistance of the design. The inference, therefore, is that the design requires excessive amounts of reinforcement and that there should be more economic approaches to the subject.

Some methods are essentially extensions of the present methods but taking a more aggressive view of soil parameters and design assumptions, whilst some take a much more fundamental approach. Work by Kupec et al (2008) examined the effect of changing the soil boundary conditions to modify the internal stresses within the structures, Fig. 14.

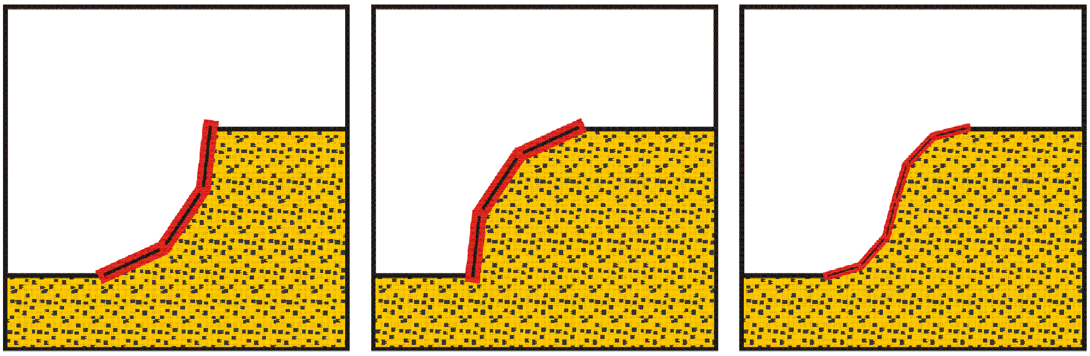

Figure 14. Variable shaped boundaries

The variable boundary shape could result in consistent reinforcement strength and spacing throughout the structures whilst also allowing the pressure on the foundation soils to be modified to suit particular conditions.

McGown et al (2004) has also put forward isochronous strain energy principles as a way to acknowledge the visco-elastic properties of polymer geogrids under different types of loading. The concept of "recoverable" energy and "locked-in" energy gave an insight into the performance of structures under dynamic loads such as traffic surcharges, vibrations and seismic conditions, Fig. 15.

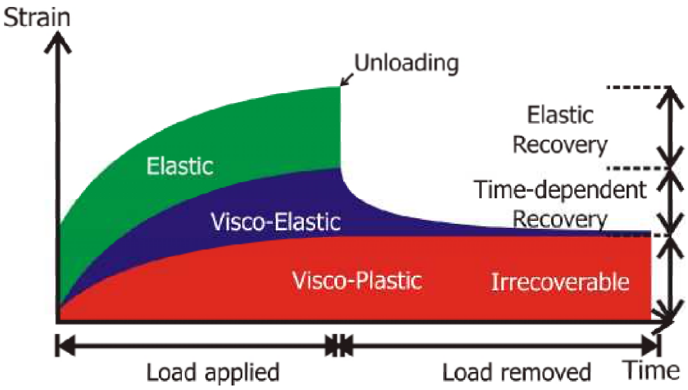

Figure 15. Isochronous Strain Energy Paths

There has been some work in recent years that challenges the basic premise of tensile strength being a primary feature of reinforcement requirements in reinforced soil structures by examining the fundamental mechanisms using numerical models. Nerheim et al (2008), Bussert (2008) and others have carried out numerical work to model actual performance of monitored structures.

WHY IS REINFORCED SOIL USED?

At the time of the first Symposium the driver for reinforced soil was one of economics. Reinforced soil was providing economic solutions for applications of access over soft soils, for the steepening of side slopes of highways to increase the useable area without increasing the footprint, for reinforced soil walls etc. As time has passed other considerations have become more important, particularly the subject of carbon emissions. Contracts are including clauses on the carbon produced by the construction operation and this is, of course, includes of the construction materials. Some of the traditional construction materials produce a large amount of carbon in their production and application and an assessment of the total carbon emissions in a project is now playing a very large and decisive part in the procurement process for civil engineering construction projects

SIGNIFICANT STRUCTURES, WALLS AND SLOPES

The use of geogrids in structures and stabilisation projects all around the world has demonstrated the flexibility and economy of these applications. Examples of reinforced soil steep slopes and walls have shown significant increases in height with single tier walls now constructed to well over 20m and multi-tier structures over 50m. Steep slopes have also shown the same development, Figs. 16, 17 and 18

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Figure 16. Very high steep slope

Figure 17. 20m high vertical wall

Figure 18. Tiered structure

As well as increases in dimensions the flexibility in terms of appearance and the proof of durability in extreme environmental situations have also been utilised to great effect. The ability to generate aesthetic features to satisfy the aspirations of more innovative architects has resulted in some very interesting visual effects, Figs. 19 and 20.

Figure 19. Aesthetic structures

Figure 20. Variable form

SIGNIFICANT PROJECTS, ROADS AND RAILWAYS

Whilst the design methods may still be predominantly empirical there has been significant use of geogrids in major civil engineering construction of, for example, wind farm access, port pavements, railways and asphalt pavements, Figs. 21 to 24.

Figure 21. Wind farm access

Figure 22. Heavy duty port pavements

Figure 23. Airport runway resurfacing reinforcement

Figure 24. Railway ballast stabilisation

CONCLUSIONS

Over the last 25 years there have been significant developments in the applications and usage of geogrids in civil engineering construction. There appears, as we will no doubt hear later in the papers and presentations, to be a large gulf between the assumptions used in the design of these applications and the actual mechanisms that are occurring in our structures and pavements. The last 25+ years have shown that we can safely design these applications and extend the scope by using the present methods but as that extrapolation increases it becomes more important to understand the actual mechanisms. At present the anticipated deformations of a structure are not predicted accurately by the design methods and assumptions.

The last 25 years have shown us that geogrid reinforced soil structures and pavements perform well, we now need to fundamentally understand why.

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