# Parameters required for performance based design of geogrid reinforced piled embankments

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**ABSTRACT**

The use of internally or basally geogrid reinforced piled embankments to bridge potential voids and to span between piles beneath embankments on soft ground, has been steadily increasing over the past decade. Such load transfer platforms are employed to support a wide variety of loading regimes and load levels within a range of permissible deflections and limiting strains. In response to commercial demand a number of different design and construction approaches have been developed to address variations in sub-soils, supported fills and geosynthetic reinforcements. These different approaches specify widely different performance requirements. In this paper, the application range of load transfer platforms is reviewed. The operational mechanisms associated with these applications are identified and the critical properties of the sub-soils, supported fills and geosynthetic reinforcements established. The currently available design and construction processes are detailed and it is shown how these are linked to the properties of sub-soils, supported fills and geosynthetic reinforcements. Further it is shown that construction methods have a crucial role in determining the construction and post construction performances of load transfer platforms. The existing differences in design and construction approaches are related to operational loading regimes and load levels and to permissible deflections and limiting strains in the load transfer platforms. Recommendations are made on the future development of design methods and on the need to link these to construction specifications.

## 1 INTRODUCTION

Load Supporting Structures are in most cases associated with Load Transfer Platforms [LTP] for void spanning applications and constructions over soft soils. LTPs used to build over soft or very soft foundation soils can be further divided into two categories. Firstly, methods where the reinforcement is used to control the initial stability of the structure, without controlling the associated settlement, and techniques where the reinforcement is used as a part of a stabilisation system to control both stability and to prevent settlement of the structure. This paper focuses on the latter technique as the control of settlement is the critical issue in most applications, and structural stability is generally included in the analysis. Void spanning has become a new application field in areas prone to subsidence and mining. Bridging of voids was traditionally undertaken in concrete or steel in combination with piling or structural slabs. Only recently with the introduction of some national standards, i.e. BS 8006 (1995) and EBGEO (1997), this construction area opened to geosynthetics.

Earlier work on LTPs, reported by numerous researchers, Giroud et al (1988 & 1990), Russel & Pierpoint (1997), and Love & Milligan (2003), employed high strength geosynthetics in construction of such structures due to uncertainties associated with construction technique, material and system behaviour. This paper aims to describe the current construction practice for LTPs spanning voids and bridging soft soil. A revision of current approaches is then undertaken and an Alternative Design Approach is presented.

## 2 DEVELOPMENT AND APPLICATIONS

Geogrid reinforced LTPs form part of a wide range of technical solutions that are available for construction over voids and soft ground. They may be designed to provide temporary or permanent support to overlying loads and they exhibit different degrees of structural stiffness.

LTPs with integrated soil reinforcement are formed by laying a single or multiple layers of tension resistant materials within a layer of compacted granular fill or a layer of stabilised soil or combinations of both. The tension resistant materials used to date include both geotextiles and geogrids. A layer of low strength geotextile, acting as a separator, may also be included at the base of the LTP to assist with the construction process. The LTP fill is generally specified as densely compacted granular fill or heavily compacted, highly frictional and dilatant granular fill. Dilatant behaviour encourages arching and therefore increases the fill stability, Whittaker & Reddish (1989).

Where LTPs are used in conjunction with piles and ground beams or pile caps, the configuration of the ground beams or pile caps is a critical design factor. Piles may be arranged on regular square or triangular grid systems. Pile caps may be square or circular. The spacing of ground beams or pile caps must be specified in both vertical elevation and horizontal separation. The details of the construction methods and sequencing of the construction of LTPs are very important factors and must be taken into account.

## 2.1 Void spanning applications

Where LTPs are used over ground liable to subsidence, due to the future development of underground cavities, access to the site in order to construct the LTP is not usually a problem. Little deformation of the ground and so the LTP actually occurs until the void develops. Thus, most deformations will be associated with post-construction movements.

## 2.2 Bridging of soft ground

Where LTPs with piles and ground beams or pile caps are constructed over soft ground, it is necessary to gain access to the site in order to install the piles and to form the piles caps, prior to the construction of the LTP. In order to install the piles, it is necessary to provide a stable working or piling platform over which the piling rig may travel, set-up and undertake the piling installation. This provision of a piling platform using a low strength geotextile separator layer covered by granular fill is one of the earliest reported applications of geotextiles, McGown & Ozelton (1973).

Control of the construction of the piling platform incorporating a geotextile separator layer, is widely recognised as being critical. The geotextiles must be laid out on ground that has been cleared of sharp objects, which would puncture it. The fill must be carefully placed over the geotextiles without horizontal shearing as this might cause tearing. The fill should be carefully levelled and compacted to prevent bursting of the geotextiles. If these procedures are not followed then the geotextiles layer may fail and the compacted fill may penetrate into the soft soil beneath. The penetration of the fill into the sub-soil disrupts the upper layers of the soft soil and generally weakens them. It may also result in the placement of much larger depths of fill than would otherwise be expected and/or be specified.

For LTPs with piles and ground beams or pile caps, the installation of piles follows on the laying of the piling platform. The construction plant used during the piling operations must be compatible with the load carrying capacity of the piling platform. The piles must be located at their correct positions within set tolerances and must be installed to the correct specifications, i.e. length, resistance, or set. The construction of the ground beams or pile caps follows on from the cutting back of the piles to a predetermined level. Strict limitations are placed on the tolerances of the vertical elevations of the top of the ground beams or pile caps, on their overall dimensions, on their spacings and their connections to the pile. An important construction feature is the excavation and storage of the fill. Making mounds of fill over the unsupported piling platform must be avoided, as this may over-stress the sub-soil and cause local failures.

The tension resistant materials in the LTP may be placed as a single layer or as multiple layers, i.e. basal or internal reinforcement. Invariably the single layer or the first layer of multiple layers is placed at or close to the top of the piling platform fill. Generally, the thickness of the LTP reinforced with tension resistant materials is at least equal to the horizontal distance between the ground beams or the pile caps to allow soil arching to develop. Deformation of the original ground primarily occurs during the construction stage. Both the tension resistant materials and the fill are subject to significant strains during this stage.

## 3 INTERNAL SUPPORT MECHANISMS

It is important to distinguish that the development of strains with time in construction works over voids and soft ground is very different due to the timing and magnitude of strain development. This influences the internal support mechanisms of the LTP. The supporting mechanisms generally associated with LTPs are Spanning (the geosynthetic is assumed to work as a tension membrane without taking the reaction of the soil into account); Composite System (full interaction between the soil and the geosynthetic); and Arching (the soil acts as a dome - the shape of this dome is a matter of engineering judgement and generally is assumed to be either semi-circular, parabolic or pyramidal).

It may be noted that the three mechanisms of Spanning, Composite System and Arching used to describe the performance of LTPs are not alternative approaches that may be used for the design of an LTP operating in a particular application. Rather they describe different stages in the development of strains in an LTP and are therefore appropriate to different application situations, Saathoff et al (2002). The links between the progressive deformation process in LTPs, the operational mechanism and the design approach are shown in Figure 1 and may be described as follows:

- The Composite System is better described as the *Stiff Composite Beam* design approach. It involves the use of an extremely stiff beam of steel, reinforced concrete or geosynthetic stabilised soil. It involves very low strains in the beam and so very low central deflections. The overlying loads are nearly uniformly distributed across the pile caps and the beam.
- The Arching mechanism is better described as the *Tied Soil Arch* design approach. It involves the use of moderate to high stiffness tension resistant materials interlocked with a highly frictional and dilatant fill. As the tension resistant material deforms and central deflections occur, so the granular fill forms a soil arch, tied together by the tension resistant material. The majority of the overlying loads are then carried directly by the pile caps.
- The Spanning mechanism is better described as the *Tension Membrane Support* design approach. It involves the use of high strength, moderate to high stiffness, tension resistant materials. The fill need not be strong nor highly dilatant. The tension resistant material deforms to such an extent that soil arching, already poorly developed in the poorer quality fill, collapses and the majority of the overlying loads are carried directly by the tension resistant material.

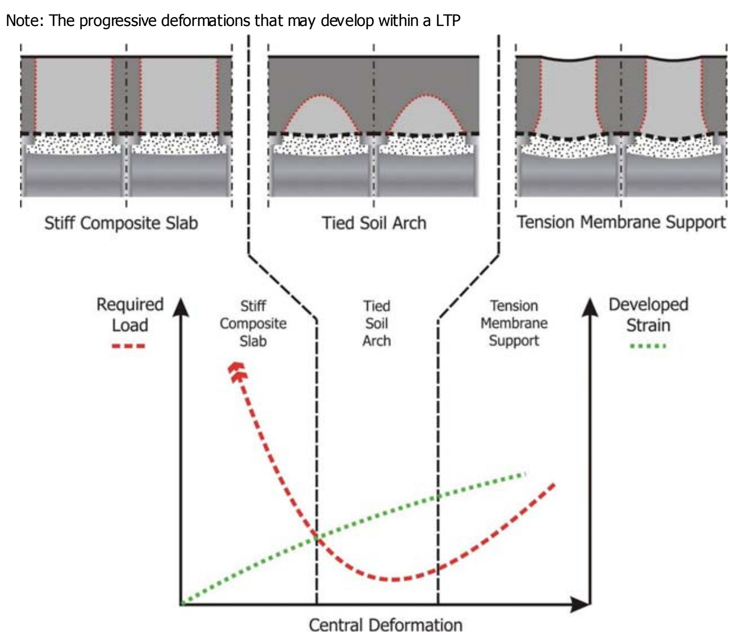


Figure 1 Classification of operational mechanisms

## 4 CURRENT DESIGN METHODS

There are numerous design methods and theories for the design of LTPs over voids or bridging soft ground. These methods differ in many ways in their core assumptions. Thus they require widely different tensile loads to be resisted by the reinforcing elements. Design methods for LTPs over voids are generally different from those bridging soft ground. The key difference in this case is the timing of strain development under operational conditions.

Giroud et al (1990) relates to deformation of the geosynthetic under loading, which is modelled to behave like a Tensioned Membrane with soil acting as a surcharge. BS 8006 (1995) is based on Limit State Design and the presence of the reinforcement provides Serviceability Limit State criteria. Both design methods identify correctly that there is little if any straining prior to void opening within the reinforced soil mass.

BS 8006 (1995) and the Industrial Design Method, after Bell et al (1994), generally represent the upper and lower boundary conditions for the determination of the reinforcement tension in a LTP bridging soft ground, Love & Milligan (2003). The main differences between both methods relates to reinforcement location, the developed strains within the reinforcement and the load shedding mechanism. The Industrial Design Method allows for highly compacted dilatant granular fill and multiple internally located reinforcements with a limiting strain of up to 5 per cent at the end of the design lifetime and it employs load shedding via soil-arching. BS 8006 allows for single basally located reinforcement with 6 per cent initial strain and further 2 per cent long-term creep strain, and load shedding mechanism is based on Marston's work on positive projecting conduits. It may be noted that calculated reinforcement tension may differ by two orders of magnitude. This suggests that these design methods are either overly conservative or unsafe, respectively, Love & Milligan (2003).

## 5 DEVELOPMENT OF AN ALTERNATIVE DESIGN METHOD

In order to develop an alternative design method extensive experimental testing was undertaken and design input parameters were critically reviewed. The alternative design method was developed for LTPs with piles and pile caps bridging soft ground and voids spaces. It was aimed at identifying key factors for vertical load shedding and to allow an assessment of the short-term and long-term load carrying capacity of the reinforcement through direct load testing, Kupec (2004).

The approach adopted for the identification of the vertical load shedding was similar to that used to assess subsidence behaviour of room and pillar mining in stratified mineral deposits, Whittaker & Reddish (1989). In a similar manner to piling beneath embankments, pillars may be formed on a symmetrical (square grid) or staggered (triangular grid) layout. In mining engineering, staggered, (triangular grids), are preferred as they are known to promote stability and decrease the potential for subsidence. Thus, a triangular piling layout for piled LTPs was suggested.

Roof collapses in room and pillar mine layouts are generally progressive. The strata above the room initially act as a stiff beam, but this may deform and weaken with time until there is a local collapse. The strata immediately above may then form progressively larger arches, which support the overlying strata. These arches may subsequently deform to such an extent that a further collapse occurs and a collapse chimney may form creating a depression or sometimes a sinkhole on the surface. It can be appreciated that the above progressive formation of mining subsidence involves the three mechanisms of deformation identified by Saathoff et al (2002).

Experience gained in the mining industry, review of published information and experimental data indicate that soil arching is governed by the shear strength and bulking (dilatancy) properties of the fill and the size of the supported area. Generally the design engineer specifies highly competent dilatant reinforced fills and therefore it is inferred that a soil arch will form. Based on extensive FEM analysis undertaken by Saathoff et al (2002), and small-scale model testing, a circular arch was adopted. The size of the supported area for each pile or pile cap was based on assumptions used for the determination of the area of influence for Prefabricated Vertical Band Drains in consolidation applications. Large-scale testing indicated that square pile caps increase reinforcement stresses at their corners and generally cause premature failure. Thus, circular pile caps are recommended.

The proposed Alternative Design Method allows the use of single or multiple layers of basal reinforcement or multiple layers of reinforcement at different levels within the fill. Many forms of anisotropic uniaxial or isotropic biaxial geosynthetic reinforcements may be employed to span the area between pile caps. Preliminary large-scale testing of biaxial geogrids employed in LTP construction indicated that material properties determined by uniaxial testing could be readily employed by adopting an effective loading width of the geogrids, in each orthogonal direction, of 0.80 times the width of the pile cap (Kupec 2004). Thus, it is suggested to determine the load-strain-time behaviour of the reinforcements by using isothermal isochronous load-strain curves, easily available from manufacturers.

It is very important to specify short-term and long-term limiting strains in order to satisfy performance requirements. The alternative design method allows various strain limits in the reinforcements to be adopted. However, in order to ensure that the soil arch is not disrupted a maximum long-term reinforcement strain of 6 % has been suggested.

## 6 COMPARISON BETWEEN ESTABLISHED AND ALTERNATIVE DESIGN METHODS

In order to determine differences between different design methods computer aided design software was written and outputs were compared. The input parameters and dimensions were chosen after extensive discussions with international practitioners in order to represent typical LTPs.

For LTPs spanning voids, the void shape and diameter were similar to voids found in former coal mining areas in Scotland, Germany and New Zealand. It may be noted that voids in karst limestone may exhibit significantly larger diameters and were therefore not considered in this study, as geosynthetics are unlikely to be a safe and economical solution in this application. The comparison between the upper and lower bound design approaches, see above, and the alternative design method indicated that:

- Post-construction deformations are very small prior to void opening
- The load shedding mechanism once voids open differs significantly
- The calculated reinforcement tensions vary over a wide range
- The calculated reinforcement tensions vary significantly with basally or multi-layer reinforcements layouts

For LTPs bridging soft ground the design input parameters were based on actual projects within the European Union. In particular, a LTP project with piles and pile caps over very soft peaty ground that was constructed in 1998 was considered for comparison. The comparison between the upper and lower bound design approaches, see above, and the alternative design method indicated that:

- The assumed load shedding mechanism greatly influences the calculated reinforcement tensions
- The calculated reinforcement tensions vary over a very wide range (up to two orders of magnitude) depending on whether basal or multi-layer reinforcements are employed
- The central deflections and percentage load carried by the reinforcements are very similar for the Industrial Design Method and the alternative design method, as both consider soil arching to occur
- The central deflections and calculated reinforcement tensions were greatest for the BS 8006 design method as expected from a Tension Membrane Support design approach where no soil arching is considered
- The applied pressures to the subsoil below the first reinforcement layer are very similar for all three design methods

## 7 DISCUSSION AND CONCLUSIONS

The overall philosophy of BS8006 (1995) is based on a quite different load-shedding mechanism from those adopted in other design methods and approaches. To some extent, this is due to a different spanning mechanism employed in BS 8006 compared to the other design methods. Additionally, the Industrial Design Method, as well as other methods, uses multiple reinforcement layers to distribute the stresses, whereas, BS 8006 relies on basal reinforcement only. Thus, an Alternative Design Method must be able to incorporate both approaches.

BS 8006 does not specify the need for a highly compacted, frictional and dilatant fill, which the Industrial Design Method, as well as other design methods including the Alternative Design Method make mandatory in order to establish the Tied Arch Support mechanism required for load shedding.

The Alternative Design Method developed for this investigation shows that reinforcement strength requirements indicated by BS 8006 do not match the Industrial Design Method. In fact, they are based on quite different operational mechanisms. This confirms findings reported previously that BS 8006 and the Industrial Design Method represent boundary conditions with respect to strength requirements.

BS 8006 allows for greater limiting strains in the reinforcement than does the Industrial Design Method. BS 8006 was intended for many different types of geosynthetics, some quite extensible, whereas, the Industrial Design Method was intended for a specific range geogrids. Additionally, the long-term strains are limited to 5% to prevent a change in support mechanism. For the same reason, the strains at ULS conditions for the Alternative Design Method were limited to 6%.

The analysis of the construction process indicated that construction strains need to be taken into account for embankments over soft clays using piles and pile caps. Since a significant proportion of strain are developed during the construction process.

Experimental data indicated that for the basally reinforced LTPs constructed with competent dilatant engineering fill, the loads in the tension resistant material are much less than required by the BS 8006 design approach. Thus, the BS 8006 design approach must be viewed as being extremely conservative for LTP design as it considers poor quality fills only.

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