EMBANKMENT SUPPORT SYSTEMS INCLUDING GEOSYNTHETICS

UTILIZAREA MATERIALELOR GEOSINTETICE LA FUNDAREA RAMBLEELOR

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ABSTRACT. Geosynthetic reinforcements are now being incorporated into structural support systems for embankments constructed over potential voids or soft soils. The geosynthetic reinforcements interact with the embankment fill and underlying ground beams or piles and pile caps in a number of ways to produce a variety of operational mechanisms. A number of analytical techniques have been developed which predict widely different tensile loads in the geosynthetic reinforcements. By relating the analytical models to the different operational mechanisms involved, the importance is highlighted of the progressive development of deformations in the reinforced fill on the loads in the geosynthetic reinforcements. The impact of construction procedures on this process is discussed and the lessons learned from the construction and design of conventional solutions which do not incorporate geosynthetics are identified. On these bases, recommendations are given for the future development of design codes / methods dealing with this innovative use of geosynthetic reinforcements.

REZUMAT. În prezent, armăturile geosintetice sunt utilizate pentru realizarea stratului suport necesar fundării rambleelor pe terenuri cu cavități sau pe terenuri moi. Armătura geosintetică interacționează în diferite moduri cu materialul din rambleu şi cu elementele de fundare (piloți solidarizați cu grinzi). Au fost puse la punct metode analitice pentru a estima eforturile de tractiune dezvoltate în armătura geosintetică. Din corelarea modelelor analitice cu diferitele mecanisme de interacțiune implicate a fost pusă în evidență importanța mobilizării progresive a deformațiilor umpluturii armate asupra nivelului de încărcare al armăturilor geosintetice. Este discutată influența tehnologiilor de execuție asupra acestui proces şi sunt prezentate învățămintele ce se pot trage din practica de execuție şi proiectare a soluțiilor convenționale, ce nu includ geosintetice. Pe aceste baze, sunt date recomandări privind elaborarea viitoarelor normative de proiectare sau metode de calcul referitoare la această utilizare inovantă a armăturilor geosintetice.

1 Introduction

Engineers are frequently asked to build embankments over potential voids or soft soils. The classical problems are the lack of stability of the side slopes and edges together with excessive overall and / or differential settlement of the central area of the embankment. For embankments over potential voids side slope, edge and central area stability must be ensured at all times. For embankments over soft soils, most frequently the critical period for side slopes and edge stability is during or soon after the end of construction. In contrast, central settlement during construction over soft soils, is rarely of concern, however, post-construction overall and differential settlements may cause problems with sub-soil structures, pipes, culverts and the surface profile of the central embankment.

The design and construction of an embankment generally requires compliance with specifications laid down by a Client. These often prescribe the final height of the embankment at the end of construction, the maximum post-construction overall and differential settlements, the maximum area of land to be occupied by the embankment and budget costs. For the works to comply with all these requirements, very often combinations of various ground improvement techniques and construction methods require to be employed. Thus combinations of vertical drains, dynamic compaction, stone columns, lime stabilised columns, excavation and replacement of poor soils, piling, ground beams, ground slabs, construction platforms, geocell mattresses, basal reinforcement, load transfer platforms, edge reinforcement, berms, lightweight fills, preloading and stage loading, may be employed. Many of these ground improvement techniques and construction methods incorporate geosynthetic products which act as separators, filters, drains or reinforcements. In some cases they simply replace conventional materials to improve technical and / or cost efficiencies, however, in other cases they provide alternative innovative solutions.

In this paper, the use of geosynthetic reinforcement materials in various innovative structural support systems for embankments are described and compared to more conventional systems which do not incorporate geosynthetics. The technical lessons to be learned from the use of the more conventional structural support systems are identified and related to the design and construction methods for embankments including geosynthetic reinforcement materials. The operational mechanisms applicable to geosynthetic reinforced fill layers in embankments are detailed and shown to be related to the stiffness of the structural support system at the base of the embankment and the frictional / dilatancy properties of the reinforced fill. Next a critical assessment is made of the currently available analytical approaches and it is shown that they are generally based on case specific, empirical design approaches. Thus more rigorous analytical methods are required. It is suggested that these will be based on FEM analysis, but that it will be necessary to employ an appropriate closed-form analysis as an initial / check design approach. A closed-form solution is suggested which is based on the analysis of old mining subsidence problems. This is shown to provide a design output which lies between existing upper and lower bound solutions. Discussion on the points raised and recommendations for future developments are then set out.

2 TYPES OF GEOSYNTHETIC REINFORCEMENT

In the 1950's the modern form of soil reinforcement was introduced by the French company 'Terra Armée'. It consisted of treated metallic strips or bars laid horizontally in granular fill, these metallic reinforcements were connected to facing elements and anchored in granular soil. The manufacturing of synthetic polymeric reinforcements was only possible due to advances in the polymer industry in the late 1950's and early 1960's. The initial forms of "Geosynthetic Reinforcements", were straps, woven or non-woven products, so called "Geotextiles". In the 1980's the first forms of mass produced polymeric reinforcements from punched stretched sheets were developed, Mercer (1987), and are known as "Geogrids". Later further methods of manufacturing of geogrids were developed. All of these geosynthetic reinforcements may be manufactured from a wide range of polymers. They are generally extruded into fibres, strips or sheets that are subsequently drawn to alter the basic polymer properties. The process of drawing, performed at room or an elevated temperature, changes the molecular alignment and therefore increases significantly the load carrying capacity / strength and the stiffness of the polymer.

The load-strain behaviour of geosynthetic reinforcements may vary significantly in their two axes of principal stiffness. This is often associated with variations in the material and geometrical properties of the fibres, straps, bars and junctions in these directions. Thus, two classes of geosynthetic reinforcements may be identified; uniaxial reinforcements, which develop tensile stiffness and strength primarily in one direction, and biaxial reinforcements which, develop tensile stiffness and strength in two orthogonal directions.

2.1 Uniaxial Geosynthetics

Uniaxial geosynthetics usually exhibit a high stiffness in the machine direction [MD] with a very low to negligible stiffness in cross-machine direction [XMD], however, it should be noted that there are products which have their maximum properties in the XMD. The main functions of the secondary cross-members and junctions are to provide geometrical stability during transport and installation, but they may also provide the possibility of interlock with the soil in which they are placed. These uniaxial geogrids are intended for use in plane strain applications, where the secondary direction has little or no tensile loading.

2.2 Biaxial Geosynthetics

Biaxial geosynthetics exhibit significant stiffness and strength in two orthogonal directions. In these materials, the fibres, straps, bars and junctions provide geometrical stability during transport and installation and may provide interlock with the soil in which they are placed. Anisotropic geosynthetics exhibit dissimilar stiffnesses in the two principal directions. They are used in anisotropic loading conditions, i.e. where there is both a primary and secondary degree of loading /strain. Whereas, isotropic biaxial geogrids exhibit very similar stiffnesses and strengths in two orthogonal directions. They are used in isotropic loading conditions, i.e. where there is almost an equal degree of loading/strain in two orthogonal directions.

The junction types now in use for biaxial geosynthetics are: (a) entangled fibres or filaments, (b) heat or chemically bonded, laser or microwave welded straps and bars, and (c) integral junctions formed during the uniaxial or biaxial drawing of punched sheets. All types of junctions provide geometrical stability during transport and installation and to some degree enable interaction with the fill in which they are placed. Geosynthetics formed with entangled or heat-bonded junctions generally only possess adequate junction strength to transfer stresses from one set of bars to another when they are subject to significant normal confining stresses. In contrast, geosynthetics formed with welded or integral junctions most often exhibit sufficient unconfined junction strength to transfer stresses from one set of bars to another under either uniaxial or biaxial loading/strain conditions.

To date, the test methodologies employed to characterise the load-strain-time properties of geosynthetic reinforcements have involved the application of uniaxial loading, BS 6906 (1987), GRI-GG4 (1987), ISO 10319 (1993), ISO 13431 (1999) and ASTM D5262 (2002). For biaxial geosynthetics this has generally involved undertaking two separate tests in orthogonal directions.

Attempts to combine the measured properties in these two directions in order to obtain the overall biaxial properties/behaviour of geosynthetics have proven to be problematic, Böhmert (1981). Thus, biaxial testing methods have been developed, McGown and Kupec (2004).

3 Embankments including geosynthetic reinforced fills

Geosynthetic reinforced fills form part of a wide range of technical solutions that are available for the construction of embankments over potential voids or soft soils, Figure 1. They may be designed to provide temporary or permanent support to overlying loads and may exhibit different degrees of structural stiffness.

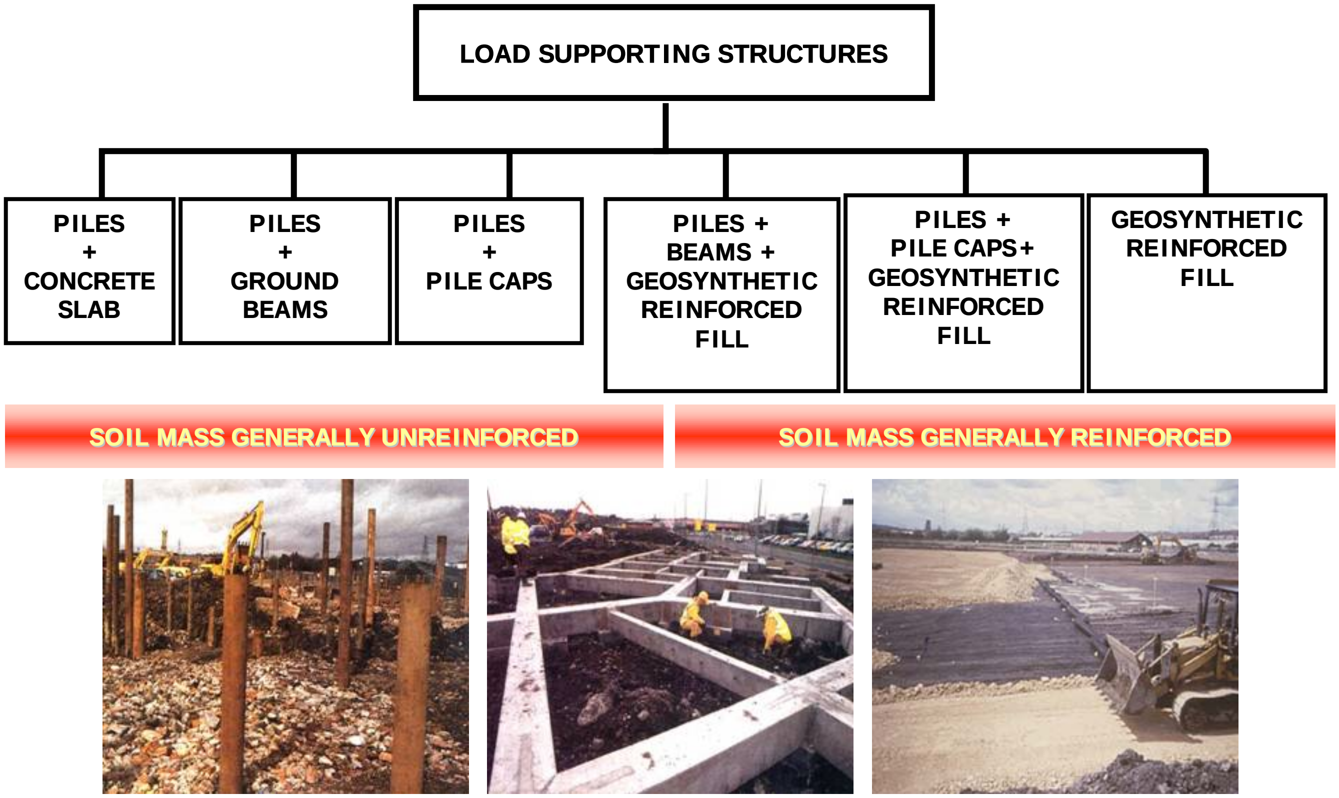


Figure 1. The range of technical solutions available for the construction of embankments over potential voids or soft soils.

Geosynthetic reinforced fill is 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 embankment to assist with the construction process. The reinforced fill is generally specified as densely compacted granular fill or heavily compacted, very strong, highly dilatant granular fill. Dilatant behaviour encourages arching and therefore increases the fill stability, Whittaker & Reddish (1989).

Where geosynthetic reinforced fills are used in conjunction with ground beams or piles and pile caps, the configuration of the ground beams or pile caps is a critical design factor, Figure 2. 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 are very important factors and must be taken into account.

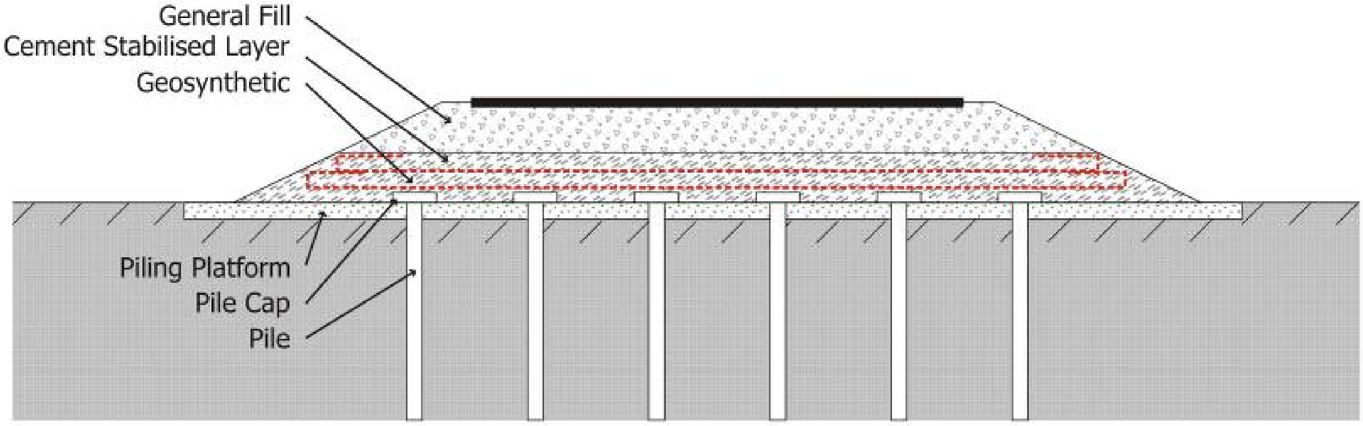


Figure 2. An embankment support system with piles, pile caps and geosynthetic reinforced fill.

3.1 Construction Over Potential Voids

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

3.2 Construction Over Soft Soils

Where embankments supported by ground beams or piles and pile caps are constructed over soft ground, it is necessary to gain access to the site in order to install the beams or piles and piles caps, prior to the construction of the embankment. Thus it is often necessary to provide a stable working or piling platform over which the construction plant may travel, set-up and undertake the construction work and / or piling installation. The provision of working or piling platforms 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 working or piling platform incorporating a geotextile separator layer, is 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 embankments with ground beams or piles and pile caps, the construction of the beams or the driving of piles follows on from the laying of the piling platform. The construction plant used during these operations must be compatible with the load carrying capacity of the working or piling platform. Where piles are used they must be located at their correct positions within appropriate tolerances and must be driven to the correct lengths and resistance, i.e. set. The construction of the pile caps follows on from the cutting back of the piles to a predetermined level. Strict limitations should be 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 an unsupported piling platform must be avoided, as this may over-stress the sub-soil and cause local failures.

The geosynthetic reinforcing materials 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 reinforced fill 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 geosynthetic reinforcing materials and the fill are subject to significant strains at this stage.

4 Internal support mechanisms

It is important to appreciate that the development of strains with time in embankments constructed over potential voids and over soft soils is very different and influences the operational support mechanisms within the fill. The operational support mechanisms generally associated with geosynthetic reinforced fill 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 judgment and generally is assumed to be either semi-circular, parabolic or pyramidal).

It should be noted that the three mechanisms of Spanning, Composite System and Arching are not separate, alternative approaches that may be used for the design of any embankment with a structural support system including geosynthetics. Rather they describe different stages in the development of strains in a geosynthetic reinforced fill and are therefore appropriate to different application situations, Saathoff et al (2002). The links between the progressive deformation process, the operational mechanism and the design approach, Figure 3, has been described by Kupec (2004), as follows:

- The Composite System relates to 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 beams or the pile caps.

- The Arching mechanism relates to the “Tied Soil Arch” design approach. It involves the use of moderate to high stiffness tension resistant materials interlocked with a strong, highly dilatant fill. As the tension resistant material deforms and central deflections occur, so the strong, dilatant fill forms a soil arch, tied together by the tension resistant material. The majority of the overlying loads are then carried directly by the beams or pile caps.

- The Spanning mechanism relates to 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.

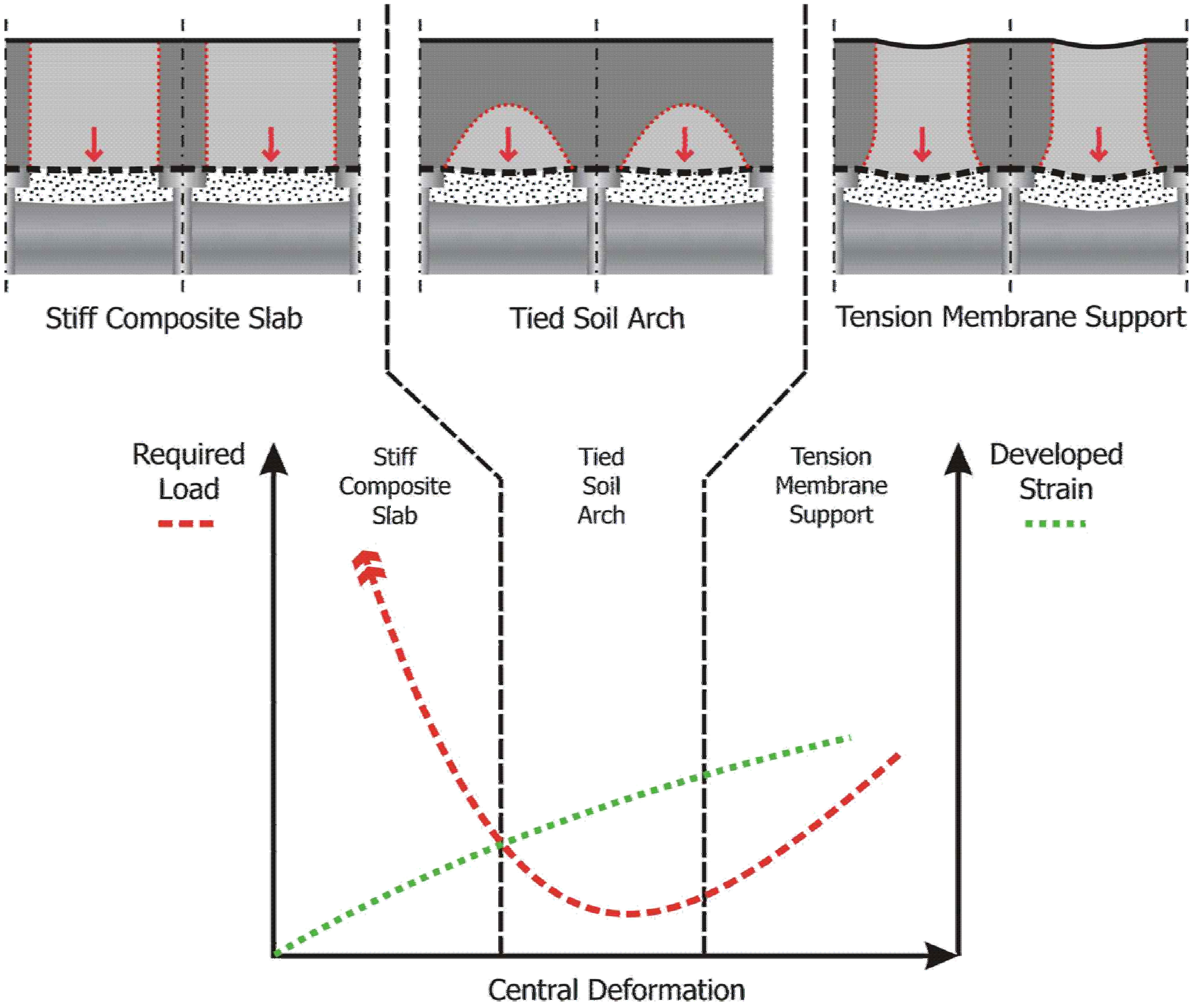


Figure 3. The links between the progressive deformation process, the operational mechanism and the design approach, (Kupec, 2004).

5 Current design methods

There are numerous design methods and theories for the design of embankment structural support systems including geosynthetic reinforced fill constructed over potential voids or soft soils. These methods differ in many ways in their core assumptions. Thus they require widely different tensile loads to be resisted by the geosynthetic reinforcing layer or layers. Design methods for embankments over potential voids are generally different from those constructed over soft soils. The key difference is the timing of strain development under operational conditions.

The model suggested by Terzaghi (1943) for load shedding related to soil arching is often employed. The Tension Membrane model suggested by Giroud et al (1990) is also widely used. BS 8006 (1995) is based on the positive projecting conduit model, employs a Limit State Design Approach and provides Serviceability Limit State criteria. The model suggested by Bell et al (1994) is based on research undertaken by Guido et al (1987) on plate loading tests on geogrid reinforced earth slabs.

BS 8006 (1995) and the Bell et al (1994) models generally represent the upper and lower boundary conditions for the determination of the reinforcement loads in embankments over soft soils, Love & Milligan (2003). The main differences between these methods relates to the location of the reinforcements, the developed strains within the reinforcement and the load shedding mechanisms.

Bell et al (1994) inherently assume the use of highly compacted dilatant granular fill and multiple layers of geosynthetic reinforcements with a limiting strain at the end of the design lifetime and employ load shedding via soil-arching. BS 8006 allows for single basally located reinforcement with an initial strain and further long-term creep strain. Further, the load shedding mechanism is based on the positive projecting conduits approach. The differences between the calculated tension forces in the geosynthetic reinforcement layers from these two design methods may be two orders of magnitude, Love & Milligan (2003).

Finite Element Methods, (FEM), of analysis are now being more and more widely employed in the design of embankments with structural support systems including geosynthetic reinforced fill. However, the application of FEM to these design problems is still at the development stage. To date, some of the input data on the properties of the constituent materials is not appropriate and insufficient consideration is being given to construction effects. Indeed, very often instantaneous loading is assumed in FEM analysis. Further in some cases, 2D and small deformation mesh elements are used when 3D and / or large deformation mesh elements are more appropriate.

FEM analysis is undoubtedly the way forward, but there is much development work required before it can be applied routinely and with confidence. In any case, a closed-form solution will be required as an initial / check design. To avoid the difficulties identified with the currently available closed-form solutions, an alternative closed-form design method has been developed by Kupec (2004).

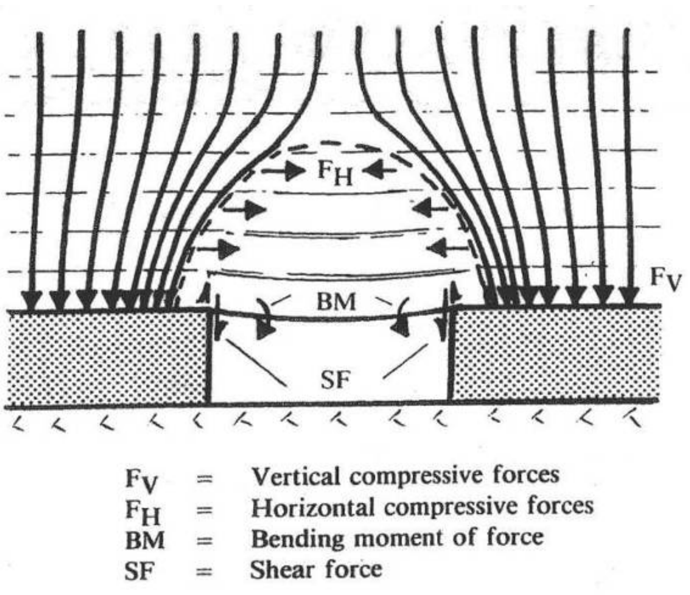
6 Development of an alternative closed-form design method

In order to develop an alternative closed-form design method, extensive experimental testing was undertaken and design input parameters were critically reviewed. The alternative design method was developed for embankments supported by piles, pile caps and geosynthetic reinforced fill over potential voids or soft soils. The aim was to identify the key factors involved in load shedding and allow an assessment of the short-term and long-term load carrying capacity of geosynthetic reinforcements 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.

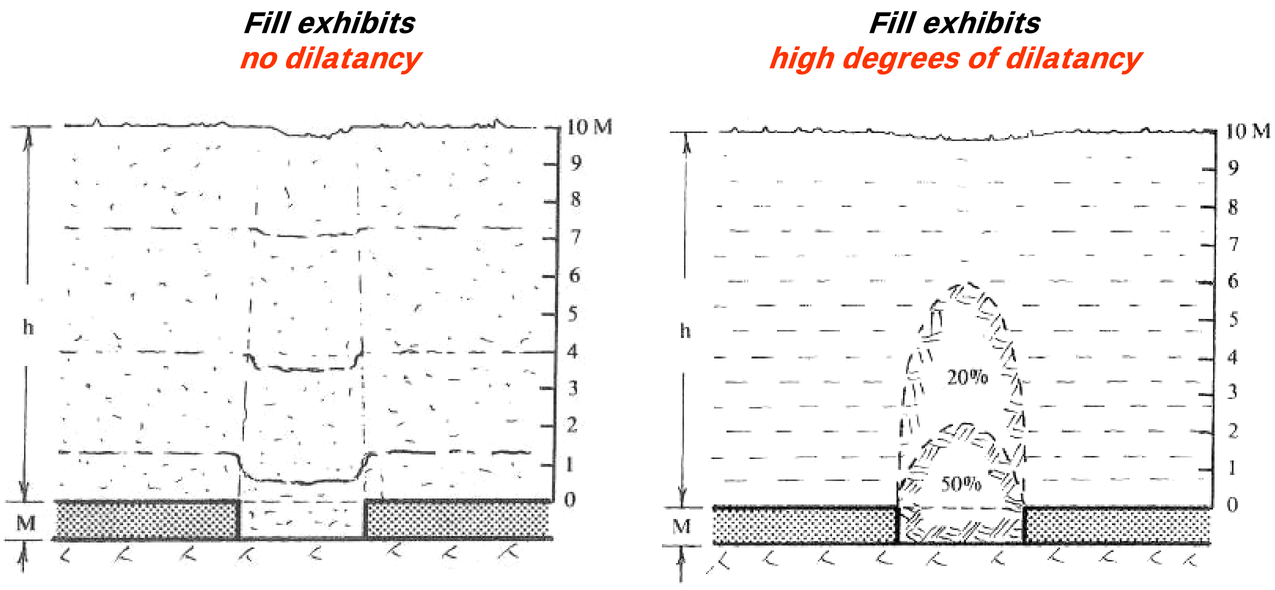
Roof collapses in room and pillar mine layouts are generally progressive. The strata above the room initially act as a stiff beam, but this may deform and weaken with time until there is a local collapse, Figure 4. The strata immediately above may then form progressively larger arches, which support the overlying strata. These arches may subsequently deform to such an extent that a further collapse occurs and a collapse chimney forms 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 judged to be the most appropriate form of the soil arch. 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, Figure 5. 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.



F_V = Vertical compressive forces
F_H = Horizontal compressive forces
BM = Bending moment of force
SF = Shear force

a) The roof acting as a beam.



Fill exhibits ***no dilatancy***

Fill exhibits ***high degrees of dilatancy***

Collapse characteristics of unconsolidated overburden into the cavity at shallow depth

Projected extent of collapse for bulking (Dilatancy) factors of 20 % and 50 %

b) Progressive collapse of the roof.

Figure 4. The behaviour of the roof in room and pillar mining, (Whittaker and Reddish 1989).

The proposed alternative design method, known as the Pillar Support Analogy, 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 the pile caps. Preliminary large-scale testing of biaxial geogrids 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. Thus, it is suggested that the load-strain-time behaviour of the reinforcements can be identified by using uniaxial, isothermal isochronous load-strain curves, easily available from manufacturers, and modifying the effective width of the reinforcement as indicated above, Kupec (2004).

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 % is suggested.

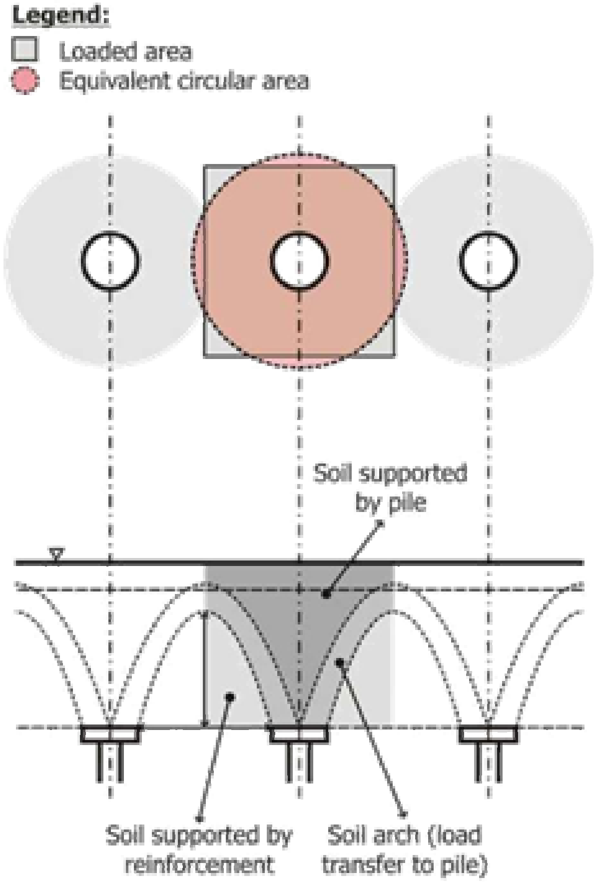


Figure 5. The pillar support analogy, (Kupec 2004).

7 Comparison of current design methods and the pillar support analogy method

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 embankment works.

For embankments over potential voids, the void shapes and diameters chosen 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. The comparison between the current upper and lower bound design approaches 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 between single basal and multi-layer reinforcements layouts

For embankments over soft soils, the design input parameters were based on actual projects within the European Union. In particular, an embankment project with piles, pile caps and geogrid reinforced fill over very soft peaty ground constructed in 1998 was considered for comparison. The comparison between the current upper and lower bound design approaches 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 Bell et al (1984) and the Pillar support Analogy, 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 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.

8 Discussion and recommendations

It has been shown that geosynthetics are innovative materials which can provide geotechnical engineers with more technically efficient and cost effective solutions to common geotechnical problems, including the construction of embankments over potential voids or soft soils. However, the lessons learned from conventional solutions which do not include geosynthetics should not be forgotten.

Currently there are a number of alternative design methods for these embankments when they are supported by ground beams or piles and pile caps overlain with geosynthetic reinforced fill. These design methods predict a wide range of tensile loads in the geosynthetics but it has been shown that they are based on quite different operational mechanisms and that they are generally case specific, empirical design solutions. They have also been shown to represent different stages in the progressive development of deformations in the structural support system of the embankment.

The design approaches in current codes and standards are very conservative and do not deal with all the possible operational mechanisms, nor do they take into account the frictional / dilatant nature of the fill material, which has been shown to greatly influence the tensile load generated in the geosynthetic reinforcement. Further, taking account of construction effects has been identified as a critical factor in the analysis of all types of structural support systems for embankments and particularly when identifying construction and post-construction deformations. Thus to fully benefit from the innovative use of geosynthetic reinforcements in the structural support systems for embankments over potential voids or soft soils, it is recommended that detailed consideration should be given to the various aspects and phases of the construction:

- The types of piles used
- The use of square or triangular piling layouts
- The piling construction sequence
- The sizes and spacings (vertical and horizontal) of circular or square pile caps
- The use of single or multiple layers of geosynthetic reinforcements and construction tolerances related to their spacings
- The use of piling platforms
- The placing and compaction of fill

Also construction and post-construction deformations should be identified within the piling platform, piles and pile caps, the reinforced fill, geosynthetic reinforcements, sub-soils or underlying rocks and the overlying fill, roads, structures and services.

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