CHAPTER 5 – REINFORCED SOIL FOUNDATIONS

Base reinforcement of soils is the addition of one or more layers of geosynthetic underneath structures constructed on soft and/or yielding soil. Typical reinforcement projects include stabilizing embankments over soft soils, column supported embankments, shallow foundations constructed over reinforced soil, and bridging voids in the subsurface or roadway shoulders. The mechanism for soil improvement can be as simple as separating native soils from fills, or can include tension membrane, soil arching, and alteration of failure mechanisms.

EMBANKMENTS OVER SOFT SOILS

When geosynthetics are used to reinforce embankments to be constructed over soft soils, one or more layers of geotextiles or geogrids are placed between the native soil and the embankment fill, while additional layers may be placed within the embankment to provide separation and reinforcement. A conceptual drawing is shown in Figure 11. Properly designed geosynthetics then reduce the tendency of certain failure mechanisms to develop, including foundation instability and lateral sliding. Ultimately, the geosynthetics are in place to speed construction (i.e., eliminating staged construction) of the embankment and to allow greater embankment heights than would be possible in an unreinforced case.

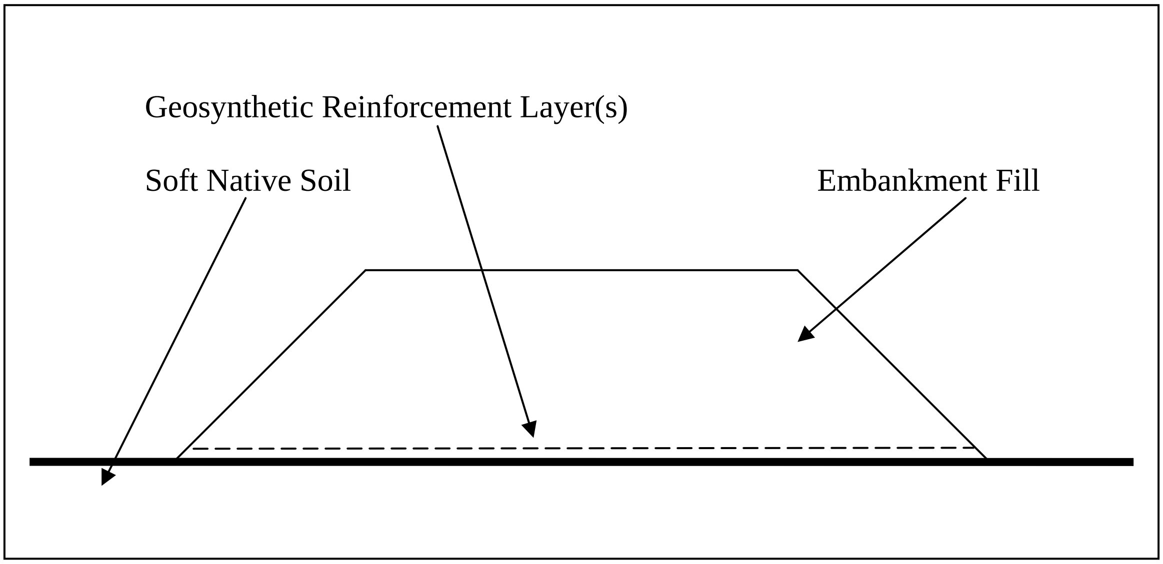

Figure 11. Diagram. Conceptual Geometry of Reinforced Embankments over Soft Soils (after Koerner 1998).

Summary of National Guidelines

Geosynthetics are used primarily for separation and reinforcement in this application. The national design guidelines in Holtz et al. (1998) provide methods to calculate required geosynthetic and fill thickness to create a stable working platform, which is often necessary to get construction equipment out onto the soft soil. The guidelines also provide a design methodology to evaluate the improvement to rotational stability and resistance to lateral spreading due to the presence of one or more geosynthetic layers. The overall bearing capacity of the foundation soil is not affected by the presence of reinforcement in this design methodology. However, the demand bearing capacity is reduced due to the distribution of the embankment load across the full width of the embankment. Lateral deformations are affected by the geosynthetic modulus; stiffer geosynthetics lead to less deformation due to lateral spreading. Rotational stability is improved through the tensile strength of the geosynthetic that adds to the resisting moment, in a manner similar to that described in Chapter 4 for reinforced soil slopes.

Seven of 11 respondents reported being involved in embankment design projects. Of those seven, five reported considering or using geosynthetics in an embankment project. As such, there appears to be some penetration of geosynthetics into an application in which a majority of respondents are involved.

Level of Maturity

Mature. These methods have been applied, with various extents,- to several embankments over nearly three decades.

Recent Advances

Gabr and Han (2005) summarized the current state of practice and suggested future enhancements to embankment design. Design methods commonly in use today were presented nearly 20 years ago, as for example the approach by Bonaparte and Christopher (1987). These limit equilibrium methods typically consider bearing capacity failure, lateral spread and deep seated, slope failures. A number of finite element studies have been performed to better understand reductions in deformation of the embankment with reinforcement (e.g. Varadarajan et al., 1999) and stresses in the underlying soil (e.g. Forsman et al., 1999). More recent studies (for example, Li and Rowe, 2001 and Sharma and Bolton, 2001) have looked at the combined effect of prefabricated vertical drains (PVDs) and geosynthetic reinforcement to expediently stabilize the embankment foundation.

Gaps in Our Knowledge

There are no prohibitive gaps perceived for this technology. Geosynthetics in separation and reinforcement functions have been used in embankment construction for more than two decades. The methods to estimate resistance to lateral spreading, overall global stability, and applied stresses as compared to the underlying soil's bearing capacity are well documented and accepted in practice. FLHP should not hesitate to implement and use this technology where economical.

COLUMN SUPPORTED EMBANKMENTS

Column supported embankments are usually constructed when a very soft soil overlies a significantly more competent one, such as a soft clay over dense sand. In these cases, driven piles, drilled piles or other soil improvement methods (vibrated concrete columns, rammed aggregate piers and deep mixed columns, for example) are used to transfer embankment loads to the more competent soil or rock layer, as schematically illustrated in Figure 12. Before the embankment is constructed, one or more layers of geosynthetics (perhaps embedded in a sand or aggregate backfill) are placed to create a load transfer platform (LTP). The LTP acts as a “beam” to transfer the embankment load away from the soft native soil, into the stiffer piles and into the more competent, deeper bearing layer.

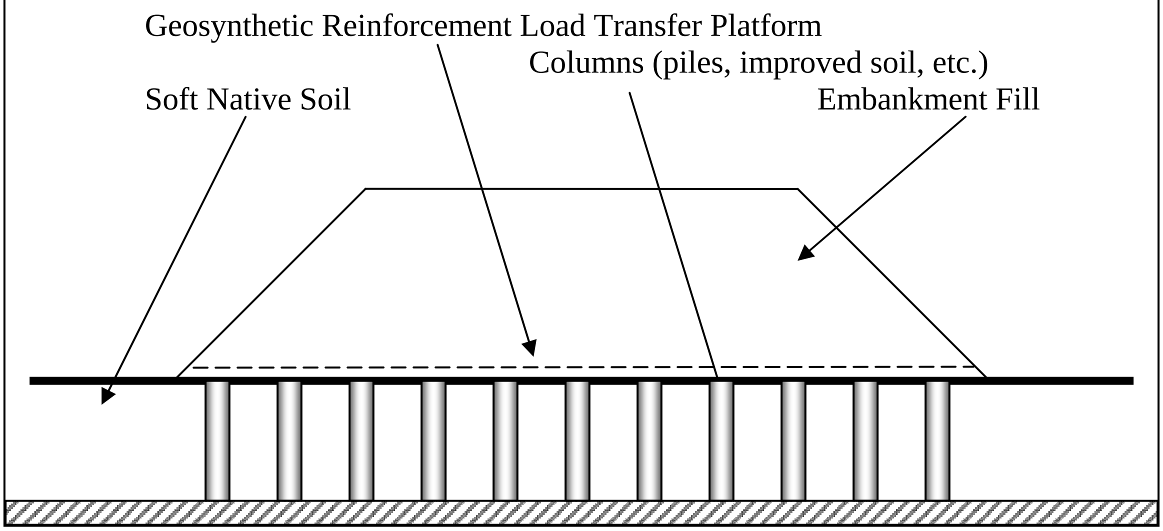

Figure 12. Diagram. Conceptual geometry for column supported embankment (after Elias et al., 2004)

Summary of National Guidelines

The national design guidelines provided in Elias et al. (2004) reviews various techniques to account for the geosynthetic reinforcement between the column-improved native soil and the embankment fill. Current design methods of the geosynthetic load transfer platforms treat the composite soil-geosynthetic section as either a catenary or a beam. Catenary theory assumes that a single layer of reinforcement is deformed and soil arches form in the embankment soil. Beam theory (the Collin Method), assumes three or more layers of reinforcement spaced vertically 0.2 to 0.45 m (8 to 18 in) apart and that the platform is at least ½ the thickness of the span between the columns. The arching that develops in the load transfer platform (beam method) is a function of the strength and confining behavior of the geosynthetic. In both the beam and catenary theory, the geosynthetic layer(s) must develop tension to withstand the weight of the soil (either embankment fill or load transfer fill for catenary and beam formulations, respectively). Design considerations for column design, lateral spreading, and global stability are similar to those discussed elsewhere.

Level of Maturity

Developing. To some extent, this is an extension of reinforced embankments over soft soils, but recent and ongoing studies are attempting to calibrate and improve the methods outlined in Elias et al. (2004).

Recent Advances

Gabr and Han (2005) surveyed the state of column-supported embankment design. They noted that geosynthetics used in the single or lowest layer of the platform are typically high-strength geotextiles or geogrids, which allows the geosynthetics to be considered as a tensioned membrane. Multiple layers embedded in the earth platform can be of lower strength, such that the resulting system can be considered as if it were a beam (Collin, 2003). As the distributed embankment load is applied on top, the bottom of the beam can have some tensile resistance that will lead to redistribution and attenuation of the applied stresses.

Design models currently attempt to estimate the stresses applied to the geosynthetic layers based on a soil arching mechanism, then estimate the required tensile resistance in the geosynthetic layers based on tensile strain properties and membrane theory. Gabr and Han (2005) summarized the available approaches for both single- and multi-layer geosynthetic systems, as does Munfakh et al. (2001) in a manner similar to shallow foundations overlying geosynthetic reinforced soils.

A number of two and three dimensional numerical models have also been developed to determine the stresses and required tensile properties of the geosynthetics (Huang et al., 2005, Han and Gabr, 2002 and Pham et al., 2004). For single layer systems, the maximum tensile stresses in the geosynthetic are predicted at the edge of the columns, which is unexpected based on tension membrane theory alone. Han and Gabr (2002) also noted that stress concentration and maximum tensile stresses are affected by the stiffness of the geosynthetic in tension and the stiffness of the column material. For multiple layered systems, the maximum tensile stresses occur near the center of the span in the bottom layer, but closer to the edges of the columns in the top layer.

Column-supported embankments for roadway applications have been constructed and reported in other recent literature. These include Mankbadi et al. (2004), Stewart et al. (2004), and Collin et al. (2005). Whyte (2005) also summarizes a number of European roadway embankment projects. A number of full scale projects have been funded or built in recent years by the FHWA and other organizations, such as Stewart et al. (2004) and "Geosynthetic Reinforced Column Supported Embankments" which began as an FHWA

Pooled Fund project in September 2003 and was scheduled to be complete in the summer of 2006.

Gaps in Our Knowledge

There is no current guidance or overwhelming field verification regarding which of the four design methods to use when designing the load transfer platform. All four methods consider the geosynthetic's strength only. The confinement benefit from the geosynthetic on the granular LTP material (if applicable for a particular grid or textile product) are not addressed in the design method. Similarly, a geosynthetic's confinement properties are not currently defined by a measurable, accepted quantity.

Gabr and Han (2005) suggest some directions for further study. The current design methods should be validated by full scale, well instrumented field measurements investigating strains in the geosynthetic, deformation characteristics, and stress distribution between column and native soil. Han et al. (2005) is an example of such field testing, combined with calibration of a numerical model. This type of validation may also be partly satisfied by ongoing studies.

Soil arching models currently employed assume rigid supports at the columns. The mechanism of load transfer from the LTP to the columns is not well understood when non-rigid columns are used**.** This is an area that requires further study. Similarly, the current design methods do not allow the designer to estimate total and differential settlements. Finally, the effect of soil resistance between the native soil and the geosynthetics layer and the effect of geosynthetics creep within the formed earth beam are also poorly understood.

To properly apply tensioned membrane theory, enough strain must develop in the geosynthetic to result in some tension. As a result, there will be some displacement that occurs to generate this strain. This deformation typically occurs during placement and compaction of the embankment fill.

SHALLOW FOUNDATIONS

Shallow foundations can be constructed on soils that have been replaced and reinforced with one or more layers of geosynthetics with the objective of reducing the size of over-excavation, as shown conceptually in Figure 13. When built atop reinforced soils, the bearing capacity or stiffness of the new system is expected to be greater than the unreinforced case.

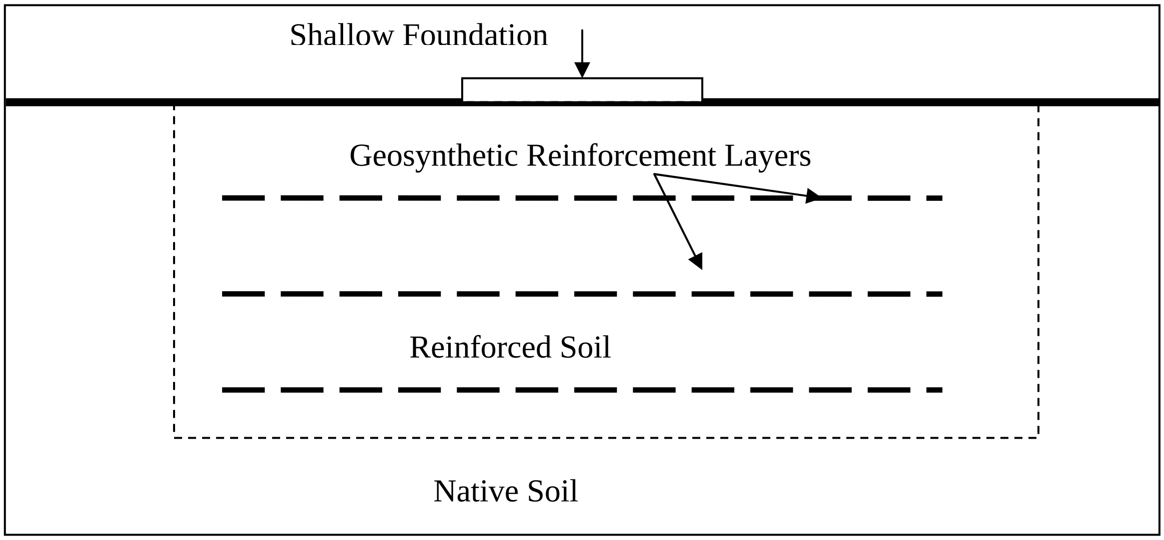

Figure 13. Diagram. Conceptual Geometry for Reinforced Shallow Foundation (after Das, 1995 and Munfakh et al., 2001).

Summary of National Guidelines

Munfakh et al. (2001) briefly discusses base reinforcement with multiple layers of geosynthetic. The manual generally recommends maximum spacing between reinforcement layers, maximum depth of the first layer of reinforcement below the footing, and the minimum width of the reinforcement relative to the width of the footing. The recommendations presented by Munfakh et al. are based on the work by Adams and Collin (1997). The Westergaard method, using a ratio of reinforced to unreinforced elastic soil modulus of 10 is recommended to estimate the reduced vertical stress distribution that is used to calculate settlement of the reinforced section.

Despite a relative lack of guidance on how to determine the amount and spacing of reinforcement in this application, four of eleven survey respondents said they had designed shallow foundations over reinforced soil. This may be a shallow foundation over an existing MSE wall or other improved wall technology.

Level of Maturity

Undeveloped. There are the beginnings of design methods that can be applied in practice for both bearing capacity and settlement, but these are largely uncalibrated.

Recent Advances

Reinforcement of fill or natural soils with geosynthetics beneath shallow foundations has been explored for nearly two decades, after the pioneering soil reinforcement work of Binquet and Lee (1975a and 1975b). Das (1995) summarized results of predominantly small model strip or square footings in test boxes filled with sand or clay. This work has identified, for the situations tested, a series of bounds on reinforcement spacing, number of reinforcing layers, total reinforced depth and reinforcement width. That is, they have identified dimensions relative to the width of the footing where no additional benefit is gained. These tests seem to suffer from unknown scale effects, as explained in Michalowski (2004), and it is unclear whether the findings are general enough to apply to other soils.

Adams and Collin (1997) performed the first (and to this date only) prototype scale tests on square footings. This work was sponsored by the FHWA, and was performed at Turner-Fairbank Highway Research Center in a large test pit filled with sands reinforced with geogrids and geocells. Their results seemed to confirm some of the relationships noted by Das and his colleagues, and showed an increase in bearing capacity could be obtained using reinforced soils.

In general, few design methods are available for determining the bearing capacity of shallow foundations. Huang and Menq (1997) suggested an empirical formula for reinforced soils after Schlosser et al.'s (1983) "deep footing" effect, where the reinforcement spreads the load with depth, such that the system can be modeled as a wider footing acting at the depth of the last reinforcement layer. The increase in footing width, ΔB, is estimated by Huang and Menq's method using Binquet and Lee's (1975a and b) lab scale testing results of soils reinforced with geosynthetics, fibers, aluminum strips, etc. The same criticism of Das's work can be applied to this analysis.

Michalowski (2004) suggested a method to estimate the upper bound of bearing capacity for a reinforced soil mass based on failure surfaces determined by plasticity theory. His results were for strip footings only, and take a form similar to a typical bearing capacity equation. This method is promising, but still requires considerable calibration and refinement before it can be adopted for use in practice.

Gaps in Our Knowledge

Clearly, the development of a relatively simple design methodology for a shallow foundation on a reinforced soil mass is important for state-of-practice implementation. Testing on a wider range of soils with either geogrids or geotextiles seems imperative, as do a wider range of instrumented full scale tests on different footing shapes. Current methods also do not quantify how to determine the optimum size and spacing of geosynthetic reinforcement.

In most cases, bearing capacity does not control shallow foundation design. Some work has been done to calibrate measured strains in large scale laboratory tests to existing settlement calculations. This must be considered for a wider range of geosynthetics to verify the assumptions of the elastic modulus increase, and for a variety of spacings.

Finally, the economics of reinforced soils should be addressed. Unless the footing is being placed over a soil reinforced for an MSE wall or other RSS structure (another possible avenue of inquiry), the construction of the reinforcement zone requires excavation of an area to a depth where the attenuated stresses do not exceed the subgrade strength. When adding in the cost of geosynthetics and backfilling with competent material, the cost of simply constructing a larger traditional footing must be considered. If the depth of excavation can be reduced, however, the shallow foundation on reinforced soils may be economical from a health and safety standpoint—shallower excavation could mean less bracing or excavation support required.

BRIDGING SUBSURFACE VOIDS

Geosynthetics have also been considered to mitigate possible settlement due to geologic discontinuities. In these cases, high strength geosynthetics are placed in areas where development of voids are feared, such as regions prone to sinkholes or where significant mining activities have occurred, as shown in Figure 14. The reinforcement is placed to bridge small and moderate sized voids by maintaining soil arching and to slow deformations to prevent collapse until the problem can be fixed for larger voids.

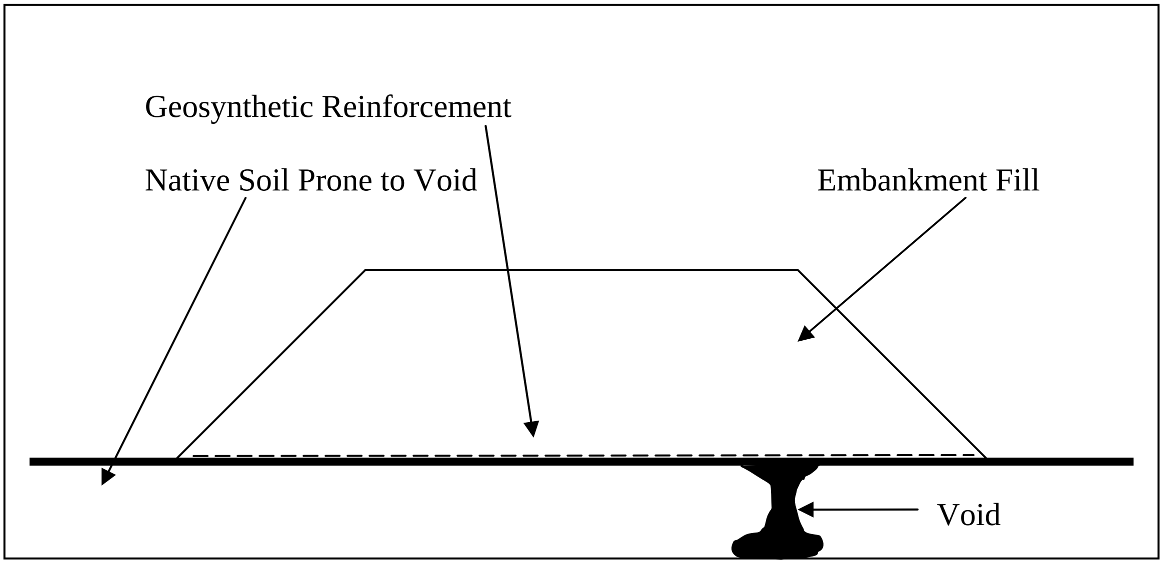

Figure 14. Diagram. Conceptual Geometry for Bridging Subsurface Voids

Summary of National Guidelines

Subsurface voids are mentioned tangentially in Holtz et al. (1998) during the embankment support section. No design method was found that addressed bridging of voids explicitly.

Level of Maturity

Undeveloped. On the national design level, no methods are currently recommended for bridging possible voids under roadways. While methods are in practice by other agencies globally, they have not been codified by AASHTO or FHWA. There may, however, be some implementation of this technology by state DOTs on a case by case basis.

Recent Advances

Recent developments for bridging subsurface voids, which could include geosynthetic reinforcement overlying a developing sinkhole, are summarized in Gabr and Han (2005). Giroud et al. (1990) suggested a model that includes pressure over an infinitely long or circular void due to arching followed by calculation of the required tension force using tensioned membrane theory. Giroud et al.'s (1990) method assumes the geosynthetic is located directly above the cavity, that the geosynthetic material's tension-strain behavior is isotropic, and that the approximation used to calculate strain in the geosynthetic over circular voids is acceptable. Drumm et al. (1990) suggested an empirical model to estimate the surface deformation due to deeper bedrock cavities such as mine voids.

Jones and Cooper (2005) reviewed the current British practice of roadway design over karst voids, which is codified in the British Standard 8006 (BSI 1995) and uses tensioned membrane theory without the addition of soil arching to determine the tension developed in the reinforcing geosynthetic. Jones and Cooper noted that this assumption results in a conservative, lower bound solution. Their parametric numerical model study concluded that differential deformation was most affected by the ratio of cover thickness to void diameter, followed by reinforcement stiffness. The numerical model indicated that reinforcement stiffness must be increased significantly to have any affect on surface deformation, and that multiple layers of geosynthetic ultimately have the same effect as a single layer of equivalent stiffness. However, these results could be a manifestation of how the reinforcement was modeled.

Gabr and Han (2005) noted that much of the work for spanning subsurface voids in the last five years has come out of Europe, where the interest is predominantly in the High Speed Rail industry. Villard et al (2000) performed a numerical and experimental study focusing on evaluating the contribution of arching and allowing the geosynthetic to reduce the vertical displacement over the void. For the high speed rail industry, the main purpose of geosynthetic reinforcement is to prevent catastrophic failure and to allow reduced speed service while construction repair activities are undertaken. In this regard, "smart geosynthetic" emerged as reinforcement layers with strain gage instrumentation. The strain in the reinforcement layers are monitored continuously to warn of impending sinkhole collapse or excessive settlement.

Gaps in Our Knowledge

No design or analysis method is available that adequately takes into account subsurface geologic discontinuities with various configurations. In this case, developing numerical models with robust representation of reinforcement to investigate anticipated deformation and efficacy of remedial measures, including geosynthetic mats, is needed. Similarly, advances in strain gage technology allow for real time monitoring of sinkhole prone areas—if an abrupt increase in geosynthetic strain is detected, a sinkhole may be forming and immediate remedial measures should be taken. For this to be the case, however, strain gage technology would have to be relatively inexpensive for wide coverage of suspect areas. This approach calls for installation of geosynthetic reinforcement over wide areas, since exact location of “future” geologic discontinuities is normally not known in advance. If FLHD were to consider this application, the geosynthetics should be considered a temporary reinforcement and warning system, not a permanent reinforcement solution.

SUMMARY

Reinforced soil foundations include embankments overlying soft soils, column supported embankments, reinforcement of soils beneath shallow foundations, and bridging subsurface voids. The use of geosynthetics in embankments overlying soft soils has been successful for many decades, and is a mature approach. Similarly, column supported embankments that include a geosynthetic reinforced load transfer platform are rapidly developing and have been field verified in both demonstration and actual projects. There is still significant work to be done before applications such as reinforcement of soils beneath shallow foundations and bridging subsurface voids can be recommended for widespread use. While some field scale projects have been completed, proven design methodologies are still needed before these two technologies can be widely used.