FAILURE OF A COLUMN-SUPPORTED EMBANKMENT OVER SOFT GROUND

William M. Camp III, S&ME, Inc., Mount Pleasant South Carolina, USA
Timothy C. Siegel, Berkel & Company Contractors, Knoxville, Tennessee, USA

ABSTRACT

As part of improvements to a roadway in coastal South Carolina, a portion of the road crossing reclaimed marshland was widened. The new lanes were constructed on a column-supported embankment consisting of sand fill reinforced by geogrid and supported by vibro-concrete columns that penetrate through the underlying very soft clays and into the local basement stratum. Shortly after construction, the roadway on the column-supported embankment began to experience distress characterized by an irregular surface with humps at the column locations and depressions in the areas between column locations. The differential vertical deformation between the high and low points was sufficiently significant that the owner closed the roadway almost immediately after completion. Forensic study illustrated that the design applied state-of-practice design techniques; however, certain design assumptions were not consistent with the fundamentals controlling the column-supported embankment behavior. This paper describes the original design, construction, and the authors' forensic study for this failure.

1. INTRODUCTION

For more than two decades, column-supported embankments (CSE) have been used to allow rapid embankment construction over soft compressible soils. A CSE consists of three components: (1) embankment material, (2) a load transfer platform, and (3) vertical elements extending from the load transfer platform to a firm stratum. The load transfer platform typically consists of granular fill with horizontal layers of a reinforcing geosynthetic. Conventional pile types were used as the vertical support element (i.e., the columns) in the early use of column-supported embankments. For more recent projects, other types of vertical elements, including soil mix columns and vibro-concrete columns, have been used in lieu of conventional pile types. A column-supported embankment is shown in cross-section in Figure 1.

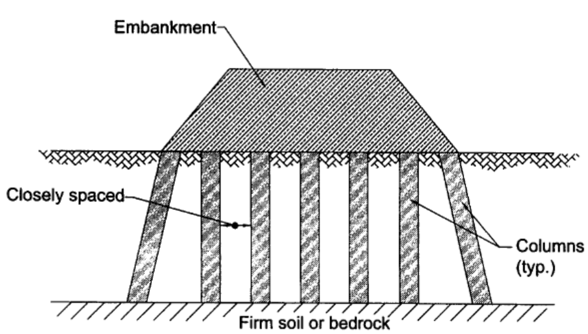

Figure 1. Column-supported embankment (after Collin, 2004)

2. REVIEW OF DESIGN METHODS

A comprehensive design and analysis of a CSE would require the consideration of a very complicated three-dimensional condition involving a complex geometry, numerous interfaces, and non-linear materials. Considering this, the available design methods make use of simplifying assumptions that need to be confirmed as part of the design process. As a minimum, the design should consider the transfer of the embankment load to the columns, the differential settlement at the surface, and the capacity of the columns.

As illustrated by the numerous recent technical papers on the subject (Collin, 2004; Collin *et al.*, 2004; Han and Collin, 2005), the CSE design methods are still evolving within the engineering community. However, a review of published literature indicates that there are two general principles common to the existing design methods:

- Soils have some ability to arch over soft zones or voids (Terzaghi, 1943). The degree of arching is related to the embankment geometry (i.e., the soil thickness required to form an arch and the size of the area that must be spanned by the arch), the strength and stiffness of the soil, and the movement within the soil mass (which is necessary to mobilize the soil strength).

- Geosynthetics can aid in the transfer of the embankment load to nearby vertical elements or columns by: (a) promoting an increase in soil arching (Collin, 2004) or (b) acting as a tensioned membrane (Giroud *et al*., 1990). The distinction between the two different purposes of the geosynthetic is crucial to the proper application of the available design methods.

3. SOUTH CAROLINA CSE CASE HISTORY

3.1 Project Background

As part of the improvements to a roadway in coastal South Carolina, a portion of the road crossing reclaimed marshland was widened. The new lanes were constructed on a column-supported embankment consisting of sand fill reinforced by geogrid and supported by vibro-concrete columns that penetrate through the underlying very soft clays and into the local basement stratum. Shortly after construction, the roadway on the column-supported embankment began to experience distress characterized by an irregular surface with humps at the column locations and depressions in the areas between column locations (i.e., dimpling). The differential vertical deformation between the high and low points (>50mm or 2in.) was such that the owner had to close the roadway almost immediately after completion. The authors were retained to review the design calculations and plans, observe the roadway conditions, and determine the events that led to roadway distress.

3.2 Ground Conditions

As illustrated in Figure 2, the ground conditions at the site consist of the following (from the ground surface): (a) an upper sandy fill layer with a thickness of approximately 2m (6.6ft), (2) very soft marsh clay with occasional interbedded sand lenses, and (3) a firm calcareous clay.

3.3 Design Review

The basic CSE design is summarized in Figures 3 and 4. The length of the CSE is approximately 310m (1017ft) and its width ranges from 7 to 20m (23 to 66ft). The vibro-concrete columns were installed in a triangular pattern with a center-to-center spacing of 2.5m (8.2ft). The 0.6m (24in.) diameter vibro-concrete columns are oversized to about 0.91m (36in.) immediately below the load transfer platform. The load transfer platform consists of 0.6m (24in.) of granular fill with three horizontal layers of Tensar BX 1200 geogrid vertically spaced at 0.2m (8in.). The typical embankment fill thickness was 1.1m (3.6ft).

The authors were responsible for review of the CSE design to determine the cause(s) of roadway distress. The *Code of practice for strengthened/reinforced soils and other fills* (British Standard 8006, 1995) provides a convenient summary of the failure modes for column-supported embankments. The ultimate limit states correspond to strength-related conditions (e.g., pile capacity and side-slope stability) and the serviceability limit states correspond to deformation-related conditions. It is the authors' conclusion that the observed deformation-related condition was consistent with the "reinforcement strain" failure mode (i.e., a serviceability limit state failure) described by the BS 8006 which is illustrate in Figure 5.

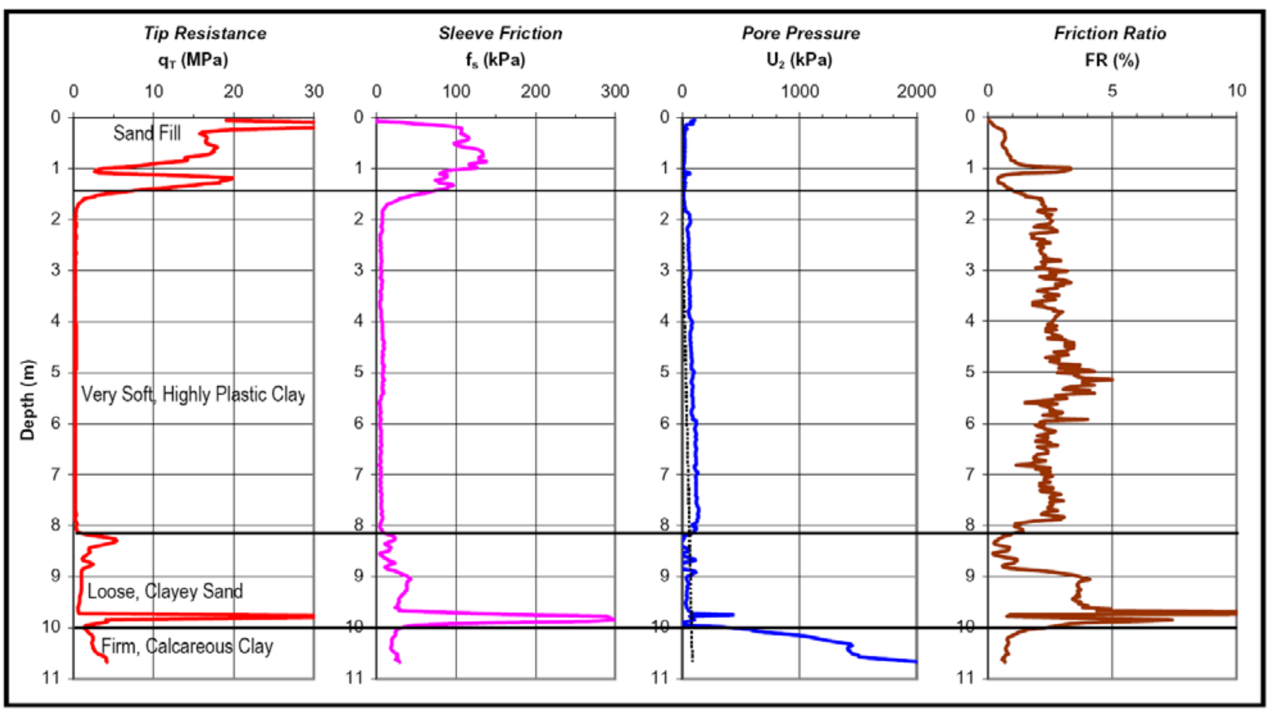

Figure 2. Ground conditions

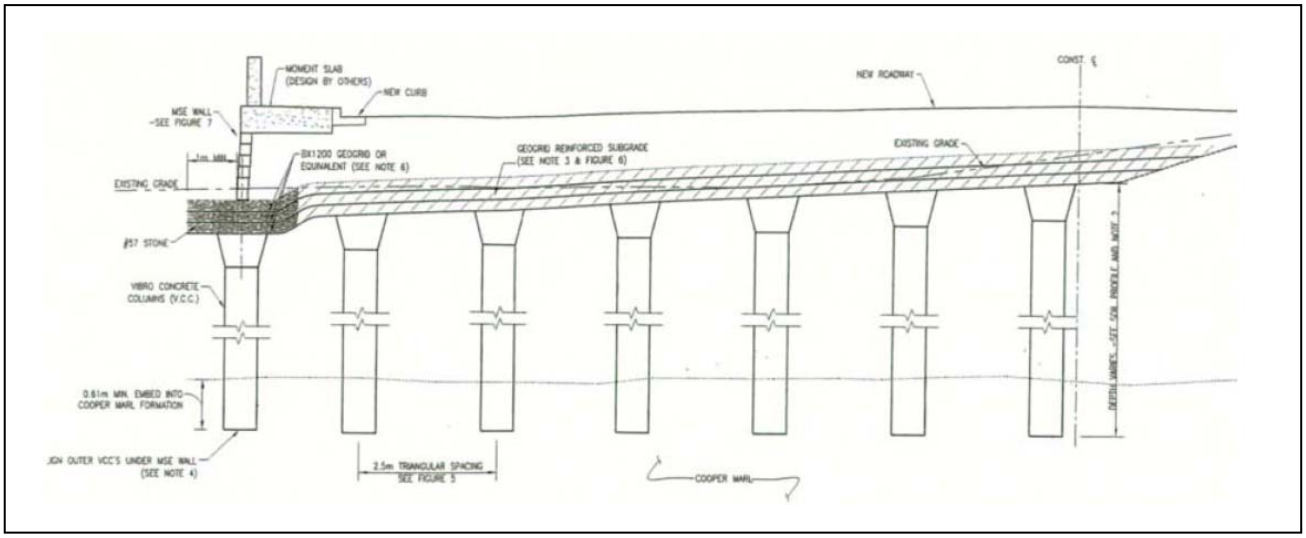

Figure 3. Conceptual drawing of the subject CSE

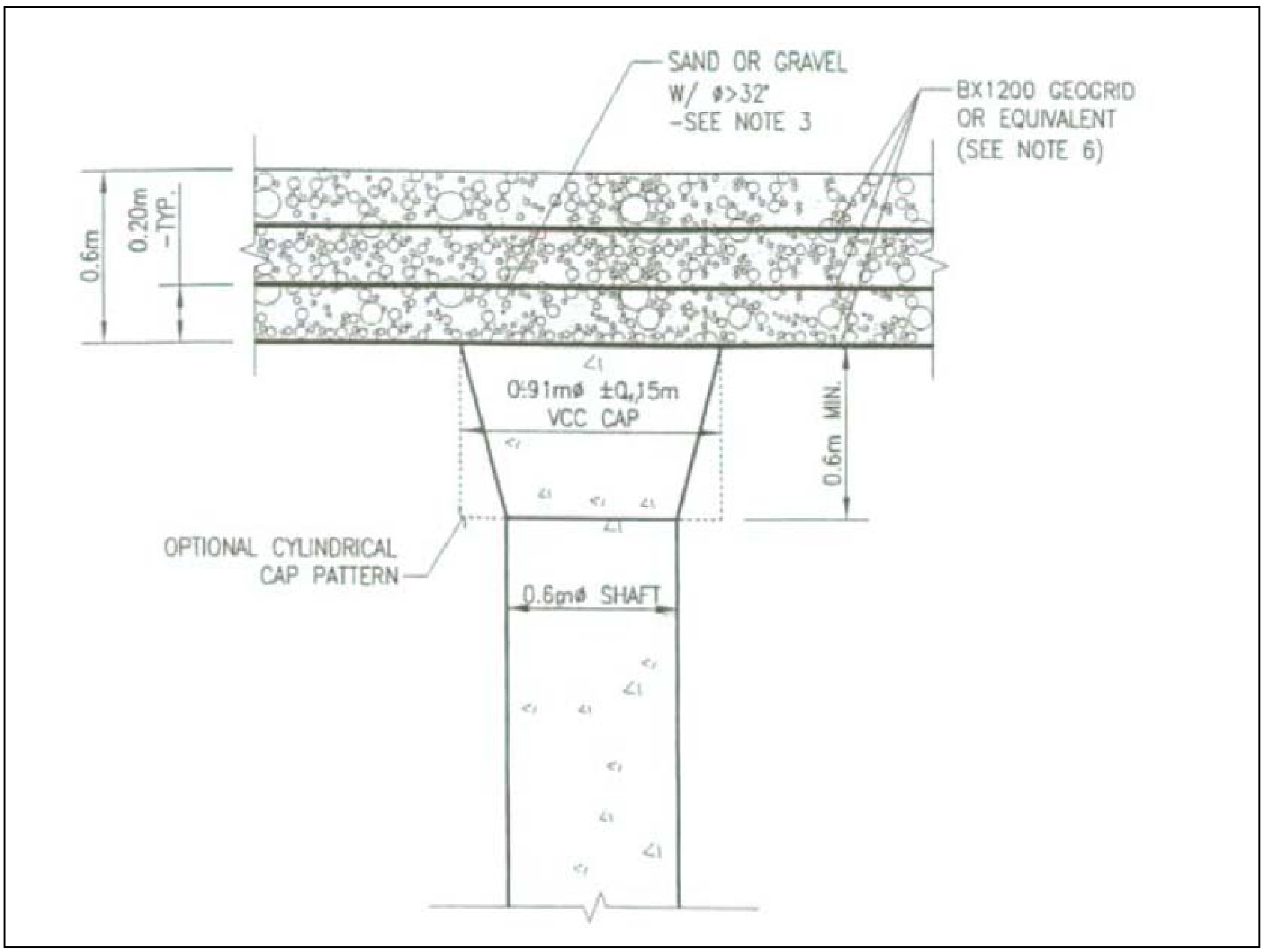

Figure 4. Detail of the subject CSE

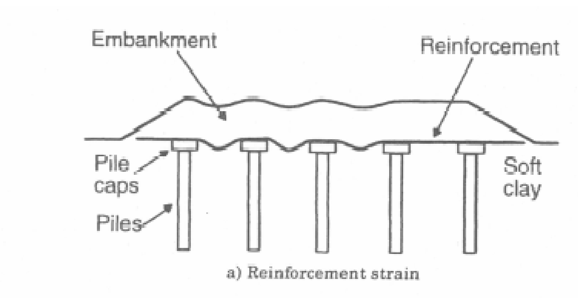

Figure 5. Reinforcement strain limit-state failure from BS 8006

The various design methods attempt to prevent a reinforcement strain failure by establishing limits on the ratio of the embankment height to the column spacing and/or ensuring that the load transfer platform is sufficiently “stiff” to limit differential vertical deformations. The embankment height-to-column relationship is related to the geometry required to fully develop arching in the load transfer platform. For a given column spacing, there exists a critical embankment height at which arching is fully developed. Above the critical height, any additional fill or surcharge loading is expected to be distributed completely to the columns with no additional loading of the subgrade between the columns (Han and Gabr, 2002). Within the various design methods, the assumed critical height ranges from a minimum of 70% of the edge-to-edge column spacing to a maximum of the center-to-center column spacing (Collin, 2004). For the column geometry of the subject CSE, the critical embankment height would range from 1.1 to 2.5m (3.6 to 8.2ft) for the various design methods. As designed and constructed, the maximum embankment height was 1.1m (3.6ft) and the majority of the embankment was too thin for arching to fully develop.

In theory, regardless of the degree of arching, it is possible to fully support the weight of the embankment on a load-transfer platform that spans the columns. Giroud *et al*. (1990) proposed a landfill design procedure that considers the ability of a geosynthetic beneath a fill to span an underlying void. This *tensioned membrane theory*, as detailed in TTN:WM3 (Tensar, 1989) was used by the original designers of the subject CSE. The intention of the design was to have the horizontal layers of geosynthetic carry the embankment load in tension and transfer the load to the nearby vibro-concrete columns. For such a design approach, it is critical to recognize that the vertical displacement of the embankment fill, the strain in the geosynthetic, and the resulting tension in the geosynthetic are interrelated. As the fill between columns experiences downward vertical displacement, the geosynthetic begins to elongate and a tensile stress is mobilized within the geosynthetic to resist the elongation. For reasons related to geometry, the tensile stress decreases as the vertical displacement (and the resulting elongation) increases. To avoid a “reinforcement strain” failure, a design must achieve compatibility between the tolerable vertical displacement and the computed geosynthetic elongation and corresponding mobilized tensile stress.

Within the original design calculations, the relationship between the strain within the tensioned membrane and the vertical displacement (i.e., embankment settlement between the columns) was not recognized. The computations of the geosynthetic strains, vertical displacements, and geosynthetic tension forces were uncoupled from one another. Due to the strain incompatibility, the actual CSE was designed and constructed with only three layers of Tensar BX 1200 geogrid with the expectation that the differential settlement would be less than 25mm (1in.). According to Tensar, the long term design strengths of BX 1200 are 3kN/m (208 lbs/ft) and 6.7kN/m (454lbs/ft) in the machine and cross-machine directions, respectively. Thus, the available combined tension in the three geogrids would be a maximum of 20.1kN/m (1362 lbs/ft).

Figure 6 correctly illustrates the theoretical behaviour of the tensioned membrane in this case. The solid line is the relationship between surface settlement and the corresponding required tension. The dashed line is the relationship between surface settlement and the geosynthetic strain (or deformed shape). As the allowable surface settlement decreases, the maximum reinforcement strain decreases and the required geosynthetic tension increases. The design objective for this project was a surface settlement of 25mm (1in.) which corresponds to a required geosynthetic tension of 268kN/m (36,750 lbs/ft). This tension force is more than 10 times greater that the value used in the original design. Considering that reinforcement of this magnitude would not be practical (e.g., 88 layers of BX1200 would be required), correct design calculations would likely have led to selection of a closer column spacing.

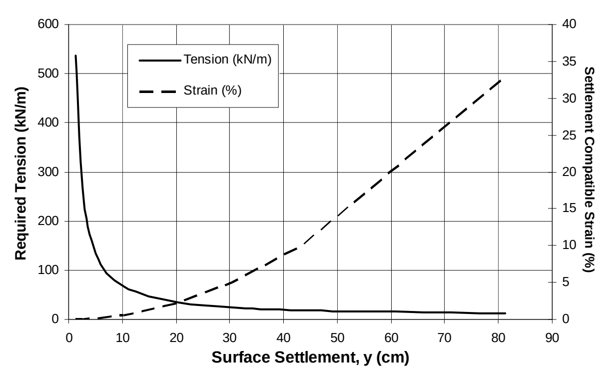

Figure 6. Strain compatibility relationship in CSE

3.4 Forensic Exploration Observations

The design deficiencies were sufficient to cause a serviceability failure but construction deficiencies further exacerbated the distress. Construction documents indicated that 25 of the 700 vibro-concrete columns were not installed. The omission of a column means that the design spacing was exceeded in some areas. The 4% reduction in the number of vibro-concrete columns likely increased surface settlement in localized areas, but the performance of the entire embankment was inadequate. Additional post-construction test pit observations by the authors' revealed several conditions that probably did not reflect the designers' intentions. There was no cut–off elevation specified for the top of the vibro-concrete columns and the as-built elevation of the top of adjacent vibro-concrete columns varied as much as 0.36m (1.2ft). As a result, the geosynthetic reinforcement was not planar nor evenly spaced in some areas. While it is understood that horizontal placement of the geosynthetic reinforcement is an important assumption of the design method, the authors' have not attempted to quantify the influence of deviations for the subject project.

4. CONCLUDING REMARKS

A column-supported embankment (CSE) was constructed across reclaimed marshland. The embankment was relatively thin (maximum height of 1.1m (3.6ft) and the vibro-concrete columns were spaced at 2.5m (8.2ft) center-to-center. Shortly after construction, the roadway surface began to deform with humps at the column locations with depressions between column locations. The distressed roadway surface distinctly appeared like the "reinforced strain" failure mode described the *Code of practice for strengthened/reinforced soils and other fills* (British Standard 8006, 1995).

The authors' forensic study revealed that the design did not properly consider the embankment height-to-column spacing guidelines and the interrelationship between embankment settlement and elongation (or strain) of the tension membrane. Because of this, the tensile resistance available within the geosynthetic reinforcement that composed the tension membrane was substantially under-designed. The authors' conclude that the primary cause of the deformation-related failure was that the embankment load exceeded the tensile resistance available in the geosynthetic layers at the elongation corresponding to the design settlement.

The authors' were requested to consider mitigation measures following the forensic evaluation. Initial consideration was given to modifying the existing CSE structure. While the roadway geometry precluded substantial changes in the embankment height, it could have been possible to add vibro-concrete columns and/or re-build the load transfer platform with a greater geosynthetic reinforcement. The owner decided that a pile-supported structure would be a more economical and reliable alternative. The distressed CSE is currently being removed and replaced with a pile-supported, structural flat-slab structure.

5. ACKNOWLEDGEMENTS

The authors' gratefully acknowledge S&ME, Inc. and Berkel & Company Contractors, Inc. for their willingness to support the preparation and presentation of this paper.

6. REFERENCES

BS 8006:1995, 1999. Code of practice for strengthened/reinforced soils and other fills, British Standards Institution, London.

Collin, J.G., 2004. "Column supported embankment design considerations." University of Minnesota, 52nd Annual Geotechnical Engineering Conference.

Collin, J.G., Watson, C.H. & Han, J., 2005. "Column-supported embankment solves time constaint for new road construction" Geotechnical Special Publication No. 131, ASCE.

Giroud, J.P., Bonapart, R., Beech, J.F. and Gross, B.A., 1990. Design of soil layer-geosynthetic systems overlying voids, Geotextiles and Geomembranes, Elsevier Science Publishers Ltd., England, 11-50.

Han, J. & Akins, K. 2002. "Use of geogrid-reinforced and pile-supported earth structures", Geotechnical Special Publication No. 116, ASCE, 668-679.

Han, J. & Collin, J.G., 2005. "Geosynthetic support systems over pile foundations" GRI-18-Geosynthetic Research and Development in Progress, Geosynthetic Research Institute.

Han, J. & Gabr, M.A., 2002., "Numerical analysis of geosynthetic-reinforced and pile-supported earth platforms over soft soils." Journal of Geotechnical and Geoenvironmental Engineering, Vol. 128, No.1, 44-53.

Kempton, G.T., Russell, D., Pierpoint, N. & Jones, C.J.P.F., 1998. "Two- and three-dimensional numerical analysis of the performance of geosynthetics carrying embankment loads over piles." Proc. 6th Int. Conf. Geosynthetics, Atlanta, Georgia.

Naughton, P.J. and Kempton, G.T., 2005. "Comparison of analytical and numerical analysis design methods for piled embankments." Geotechnical Special Publication No. 131, ASCE.

Rogbeck, Y., Gustavsson, S., Sodergren, & Lindquist, D. 1998. "Reinforced piled embankments in Sweden-design aspects." Proceedings of Sixth International Conference on Geosynthetics, 755-762.

S&ME, Inc. 2004. Report of Design Review – Virginia Avenue Roadway Widening. Charleston, South Carolina.

Stewart, M.E., Navin, M.P. & Filz, G.M. 2004., "Analysis of a column supported test embankment at the I-95/Route 1 interchange." Geotechnical Special Publication No. 126, ASCE.

Terzaghi, K., 1943. Theoretical soil mechanics, John Wiley & Sons, 510 p.

TTN:WM3 – Tensar Technical Note. 1989. Design of Tensar geogrid reinforcement to support landfill lining and cover systems, Tensar Corporation, 24 p.