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Authors: George M. Filz and Michael P. Navin				
Performing Organization Name and Address:  Virginia Transportation Research Council 530 Edgemont Road Charlottesville, VA 22903				
Sponsoring Agencies' Name and Address  Virginia Department of Transportation 1401 E. Broad Street Richmond, VA 23219				
Supplementary Notes				
<p><b>Abstract</b></p> <p>Column-supported embankments have a great potential for application in the coastal regions of Virginia, where highway embankments are often constructed on soft ground. The columns can be driven piles, vibro-concrete columns, deep-mixing-method columns, stone columns, or other suitable types. Column-supported embankments are used to accelerate construction by eliminating consolidation times that are needed for preloading and surcharging operations associated with conventional prefabricated vertical drains.</p> <p>This study has resulted in a development of new numerical stress-strain analyses to evaluate the stability of embankments supported on columns installed by deep mixing method. Such analyses reflect the multiple realistic failure mechanisms that can occur when strong columns are installed in weak soil. Detailed recommendations for performing numerical analyses are presented. The findings are also expected to apply to vibro-concrete columns, because they, like deep-mixing-method columns, are strong in compression but weak in bending and tension.</p> <p>The study also recommends the use of reliability analyses in conjunction with the stability analysis. Reliability analyses are necessary, because deep-mixed materials can be highly variable and because typical variations in the strength of the surrounding clay can induce abrupt tensile failure in columns. Additional benefit of the reliability-based design is that it permits rational development of statistically-based specifications for constructing deep-mixed materials.</p>				

**FINAL CONTRACT REPORT**  
**STABILITY OF COLUMN-SUPPORTED EMBANKMENTS**

**George M. Filz**  
**Professor**

**Michael P. Navin**  
**Post-doctoral Research Associate**

**Via Department of Civil and Environmental Engineering**  
**Virginia Polytechnic Institute & State University**

*Project Manager*

Edward J. Hoppe, Ph.D., P.E., Virginia Transportation Research Council

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## **NOTICE**

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## ABSTRACT

Column-supported embankments have great potential for application in coastal regions in Virginia where embankments for transportation applications are often constructed on soft ground. The columns can be driven piles, vibro-concrete columns, deep-mixing-method columns, stone columns, or other types of suitable columns. Column-supported embankments can be used to accelerate construction by eliminating the consolidation times that are needed for preloading and surcharging with prefabricated vertical drains. Column-supported embankments can also be used to protect existing adjacent facilities against induced settlement, such as protecting an existing pavement when an embankment is being widened.

Established procedures are available for analyzing the stability of embankments supported on driven piles and on stone columns. Summaries of these procedures are presented in appendices to this report. For embankments supported on deep-mixing-method columns, limit equilibrium methods of slope stability analysis are often used, but these methods only reflect composite shearing through the columns and soil, and they do not directly reflect the more critical failure modes of column bending and tilting that can occur when the columns are strong.

A principle outcome of this research is to recommend that VDOT engineers and their consultants use numerical stress-strain analyses to evaluate the stability of embankments supported on columns installed by the deep mixing method. Such analyses do reflect the multiple realistic failure mechanisms that can occur when strong columns are installed in weak ground. Detailed recommendations for performing numerical analyses are presented.

Another important recommendation is that VDOT engineers and their consultants use reliability analyses in conjunction with numerical analyses of the stability of embankments supported on deep-mixing-method columns. Reliability analyses are necessary because deep-mixed materials can be highly variable and because typical variations in the strength of the surrounding clay can induce abrupt tensile failure in the columns, unless properly accounted for in reliability-based design. As part of this research, a spreadsheet that facilitates reliability analyses has been provided to VTRC.

An additional benefit of reliability-based design is that it permits rational development of statistically based specifications for constructing deep-mixed materials. Such specifications can reduce construction contract administration problems because they allow for some low strength values while still providing assurance that the overall design intent is being met.

Although this research focused on columns installed by the deep mixing method, the findings are also expected to apply to vibro-concrete columns because they, like deep-mixing-method columns, are strong in compression but have low bending and tensile strength.

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### **INTRODUCTION**

A research project sponsored by Virginia Transportation Research Council and titled “Columnar Reinforcement of Soft Ground beneath Roadway Embankments” has generated two VTRC reports. This report addresses stability of column-supported embankments. A companion report addresses design of bridging layers in column-supported embankments.

Column-supported embankments are constructed over soft ground to accelerate construction, improve embankment stability, control total and differential settlements, and protect adjacent facilities. The columns that extend into and through the soft ground can be of several different types: driven piles, vibro-concrete columns, deep-mixing-method columns, stone columns, etc. The columns are selected to be stiffer and stronger than the existing site soil, and if properly designed, they can prevent excessive movement of the embankment.

Column-supported embankments are in widespread use in Japan, Scandinavia, and the United Kingdom, and they are becoming more common in the U.S. and other countries. The column-supported embankment technology has potential application at many soft-ground sites, including coastal areas where new embankments are being constructed and existing embankments are being widened.

An alternative to column-supported embankments is use of prefabricated vertical drains combined with gradual placement of the embankment fill. This well-established technique can permit construction of embankments on soft ground at a lower construction cost than by using the column-supported embankment technology. However, use of vertical drains and gradual embankment placement requires considerable time for gradual consolidation and strengthening of the soft ground, and this approach can also induce settlement in adjacent facilities, such as would occur when an existing road embankment is being widened. If accelerated construction is necessary, or if adjacent existing facilities need to be protected, then column-supported embankments may be an appropriate technical solution.

The cost of column-supported embankments depends on several design features, including the type, length, diameter, spacing, and arrangement of columns. Geotechnical design engineers establish these details based on considerations of load transfer, settlement, and stability. A separate VTRC report by Filz and Smith (2006) addresses the load transfer and settlement issues. This report addresses stability. The primary emphasis in the main body of this report is on stability of embankments supported on columns installed by the deep mixing method because (1) new embankments at the I-95/U.S. Route 1 interchange, in Alexandria, Virginia, were being designed using columns installed by the deep mixing method at the time this research project was initiated and (2) more uncertainty exists in the literature about this case than for embankments supported on driven piles or stone columns.

In the deep mixing method, stabilizers are mixed into the ground using rotary mixing tools to increase the strength and decrease the compressibility of the ground. In the dry method of deep mixing, dry lime, cement, fly ash, or other stabilizers are delivered pneumatically to the mixing tool at depth. In the wet method of deep mixing, cement-water slurry is introduced through the hollow stem of the mixing tools.

Although the focus of this report is on deep-mixing-method columns, many of the techniques described here can also be used for vibro-concrete columns because they also have high compressive strength and low bending and tensile strength. In addition, stability analysis methods for embankments supported on piles and stone columns are presented in Appendices A and B, respectively. Consequently, this report can be used as a reference for stability of embankments supported on a wide variety of column types.

This research is part of a larger project that has spanned several years of involvement by the authors. All the details of the research cannot be covered in this summary report, which instead describes the key findings and the procedures that would be used by design engineers in practice. Additional information is available in the dissertation by Navin (2005).

## **PURPOSE AND SCOPE**

The primary purpose of this research is to develop reliable procedures that geotechnical engineers can use to analyze the stability of column-supported embankments. Existing procedures are available for analysis of the stability of embankments supported on piles and stone columns, and these are presented in the appendices. Reliability-based approaches were developed for stability analysis of embankments supported on columns installed by the deep mixing method. Deep-mixed materials are variable, and this has an important impact on the procedures that should be used to produce reliable designs. The stability analysis methods presented here for embankments on deep-mixing-method columns are expected to also apply to vibro-concrete columns.

The scope of this research includes:

- A review of the pertinent literature on stability of column-supported embankments.

- Compilation and statistical analyses of data sets of strength and stiffness of deep-mixed materials.
- Limit equilibrium analyses and numerical stress-strain analyses of field cases histories and centrifugal model studies.
- Reliability analyses of slope stability for embankments supported on deep-mixed materials.
- Development of recommendations for stability analysis of column-supported embankments.

The scope of this report does not include design of bridging layers for column-supported embankments. Bridging layer design is covered in a report by Filz and Smith (2006).

## **METHODS**

This section describes the methods and procedures that were used for the literature review, data collection and statistical analyses for deep-mixed material strength and stiffness, numerical stress-strain and limit equilibrium analyses, reliability analyses, and development of analysis and design procedures.

### **Methods for the Literature Review**

The literature review was based on searches using Compendex®, Web of Science®, and other search engines, including those supported by the American Society of Civil Engineers, the Federal Highway Administration, and the Swedish Geotechnical Institute. The contents of relevant journals and conference proceedings were also surveyed. Altogether, about 500 literature sources were reviewed. A comprehensive bibliography is available upon request.

### **Methods for Data Collection and Statistical Analyses of Deep-Mixed Material Strength and Stiffness**

Based on personal contacts, and under the sponsorship of the U.S. National Deep Mixing Program, unconfined compressive strength data from nine deep mixing construction projects were collected. One of these is VDOT's interchange re-construction project at the intersection of I-95 and US Route 1 in Alexandria, Virginia. Altogether, these nine projects produced 13 data sets for analyses based on differences in construction technique, subsurface conditions, and sampling technique. In total, 7,079 strength data points were collected.

The strength data were analyzed to produce values of mean, standard deviation, and coefficient of variation for each data set. Regression analyses were applied to the data to identify controllable parameters that influence strength. After the influence of controllable trends was removed, new values of coefficient of variation were computed to better represent the inherent variability of deep-mixed materials.

The strength data were compared to four standard distributions: normal, lognormal, uniform, and triangular. Goodness-of-fit tests were performed using the Chi-squared test and the Kolmogorov-Smirnov test. Both of these tests are described in Ang and Tang (1975).

For three of the data sets, sufficient information was available to evaluate spatial correlation and compute the autocorrelation distance. The amount of spatial correlation was determined using plots of correlation versus distance. These plots, which are known as correlograms, were determined using a four-step process: (1) column coordinates were used to find the distance from each column to every other column in a data set, (2) pairs of columns were then sorted according to separation distance and stored along with the strength measurements for the columns, (3) a “lag distance” was used to collect pairs of columns into discrete bins according to their separation distance, and (4) the correlation between strength values for pairs of columns was plotted as a function of separation distance. Variowin (Pannatier 1996) is a computer program that was used to perform all four of these steps in two dimensions using the “average value” and “minimum value” methods recommended in the Variowin manual. The autocorrelation distance was determined using the procedures described by Baecher and Christian (2003). The autocorrelation distance was incorporated into the reliability analyses using the procedures described by El-Ramly et al. (2002). In the reliability analyses, the strength of deep mixed material can be assumed to be completely correlated within the autocorrelation distance and completely uncorrelated beyond the autocorrelation distance.

For the data set from the I-95/Route 1 project, complete stress-strain curves were available for most of the data points. This permitted determining modulus values and relating them to strength.

### **Methods for Limit Equilibrium and Numerical Stress-Strain Analysis**

Limit equilibrium slope stability analyses of column-supported embankments were performed using Spencer's method, as implemented in the computer program UTEXAS4 (Wright 1999). The analyses were performed using short-term undrained strengths, because this is the critical condition for slope stability of rapidly constructed embankments.

Another type of limit equilibrium analysis that was performed is for extrusion of soft clay between parallel panels of deep-mixed material that are created by overlapping columns. Such panels are often constructed beneath the side slopes of embankments and oriented perpendicular to the embankment centerline to create shear walls that are resistant to the tilting and bending failure modes that can occur for isolated columns. An analysis method for extrusion is presented in CDIT (2002) and illustrated in Figure 1. The factor of safety against extrusion,  $FS_E$ , of a prism of soft clay between panels is given by

$$FS_E = \frac{2(L_s + D_i)Bc_u + P_p}{P_a + k_h \gamma B D_i L_s} \quad (1)$$

where  $D_i$  = height of prism,  $B$  = length of prism,  $L_s$  = width of prism,  $c_u$  = mean undrained shear strength of the untreated soil,  $\gamma$  = unit weight of untreated soil,  $k_h$  = design seismic coefficient,  $P_a$  = active earth force, and  $P_p$  = passive earth force.



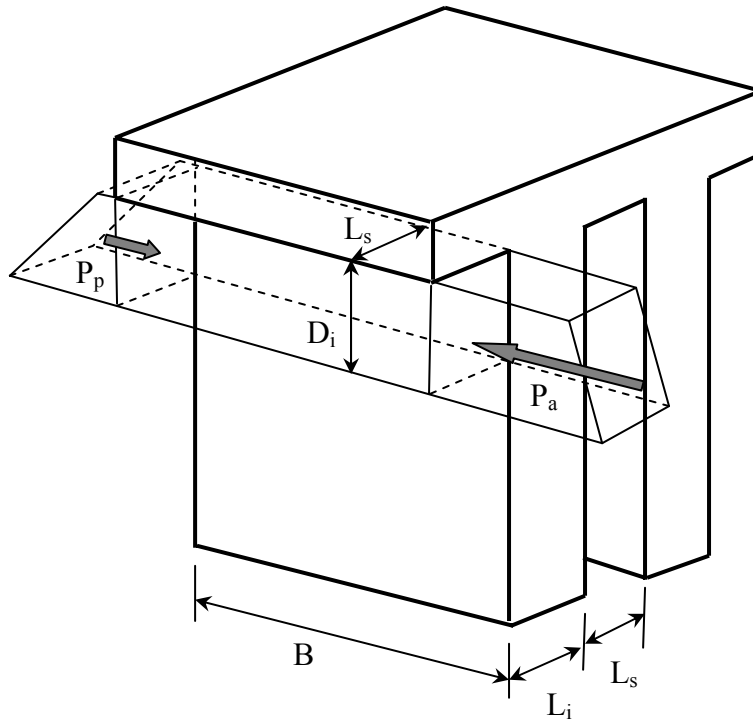


Figure 1. Extrusion of soft clay between panels (after CDIT 2002)

In addition to limit equilibrium analyses of stability and extrusion, numerical stress-strain analyses of displacements and stability were performed using FLAC (Itasca 2002a) and FLAC3D (Itasca 2002b).

FLAC and FLAC3D are finite difference analysis programs that solve the equations of motion for deformable bodies under load. FLAC performs analyses of problems in two dimensions. In this research, FLAC was used to perform plane strain analyses of embankment cross-sections to investigate deformations and stress distributions for column-supported embankments under short-term undrained conditions. FLAC3D performs analyses of problems in three dimensions. FLAC3D was used in this research to analyze the same issues for which FLAC was used, but with the full three-dimensional geometry considered.

FLAC analyses were performed not only to investigate deformations and stress distributions, but also to assess stability of column-supported embankments. FLAC incorporates an automated procedure to evaluate the factor of safety by reducing strength values to determine the condition of impending failure, at which point the numerical model is in a state of limit equilibrium. As discussed below, the advantage of performing stability calculations using a numerical stress-strain analysis program like FLAC is that multiple realistic failure modes, e.g., composite shearing, column tilting, and column bending, can all be considered in a single analysis. Conventional limit equilibrium slope stability analyses only consider composite shearing.

Specific details about the procedures that were employed in the numerical analyses using FLAC are summarized in Appendix C.

After the numerical analysis procedures were verified against field case histories and centrifugal model studies, additional numerical analyses were performed to investigate impacts of geometry and material property values on system performance and to perform reliability analyses of stability.

### **Methods for Reliability Analyses**

Reliability analyses were performed using the Taylor Series Method, the Point Estimate Method, the Hasofer-Lind Method, and the Direct Integration Method. The first three of these are simplified approximate methods, and the Direct Integration Method is an exact method that would not normally be performed in practice because of the engineering and computational time required. All four methods of reliability analysis are described in detail in Appendix D, where literature reference sources are provided. Spreadsheets have been provided to VTRC to facilitate the computations necessary for the simplified methods. In this research, reliability analyses were used with (1) stability analyses to determine the probability of slope stability failure and (2) extrusion analyses to determine the probability of failure by extrusion of soft clay between panels of deep mixed material oriented perpendicular to the embankment centerline. Appendix D contains guidance from the U.S. Army Corps of Engineers regarding values of the probability of failure,  $p(f)$ . In this guidance, a value of 0.1% is described as an “above average” level of expected performance.

### **Methods for Development of Analysis and Design Procedures**

Findings from the literature review, investigation of data from case histories, numerical analyses, limit equilibrium analyses, and reliability analyses were all used to develop recommended procedures for analyzing the stability of column-supported embankments.

An important goal of this research was to develop recommendations that employ limit equilibrium methods to the greatest extent possible because they are easy to use and familiar to all geotechnical engineers. However, in the case of stability of embankments supported on deep-mixing-method columns with typical column strengths used in the United States, the physical mechanics of the problem and the inherent material variability demand that numerical analyses and reliability analyses both be performed to develop safe and cost-effective designs. If weak columns with unconfined compressive strengths less than about 15 psi are used, then useful limit equilibrium calculations can be performed. But strengths in the order of 200 psi are often used in the United States, and numerical analyses are necessary to capture the complex failure modes that can occur for strong columns. Furthermore, customary judgments about the values of factor of safety that are needed to produce reliably safe embankments do not apply to these systems because of the high variations in factor-of-safety values that occur as system parameter values are varied over realistic ranges. Consequently, reliability analyses are needed in combination with numerical analyses to obtain a full understanding of system performance.

For these reasons, recommendations for performing numerical analyses of stability are presented in Appendix C, and descriptions of reliability analysis procedures are presented in Appendix D. In addition, spreadsheets for performing reliability analyses have been developed and provided to VTRC.

## RESULTS

This section describes the results obtained from the literature review, data collection and statistical analyses of deep-mixed material strength and stiffness, verification studies for the numerical stress-strain analyses, and reliability analyses of stability and extrusion.

### Results of Literature Review

Results obtained from the literature review are grouped into the following two categories: (1) property values and variability of deep-mixing-method materials and (2) analysis methods for stability of column-supported embankments.

#### Property Values and Variability of Deep-Mixing-Method Materials

The engineering properties of soils stabilized by the deep mixing method are influenced by many factors including the water, clay, and organic contents of the soil; the type, proportions, and amount of binder materials; installation mixing process; installation sequence and geometry; effective in-situ curing stress; curing temperature; curing time; and loading conditions. Given all the factors that affect the strength of treated soils, the Japanese Coastal Development Institute of Technology (CDIT 2002) states that it is not possible to predict within a reasonable level of accuracy the strength that will result from adding a particular amount of reagent to a given soil, based on the in-situ characteristics of the soil. Consequently, mix design studies must be performed using soils obtained from a project site. Laboratory preparation and testing of specimens is discussed by Jacobson et al. (2005) for the dry method and by Filz et al (2005) for the wet method. Even relatively modest variations in binder materials may result in greatly different properties of the mixture. Furthermore, engineering properties of mixtures are time dependent, due to long-term pozzolanic processes that occur when mixing cement or lime with soil. Design is generally based on the 28-day strength of the mixture.

Laboratory mixing is often more complete than field mixing, and the strength of laboratory mixed specimens can be greater than the strength of field mixed materials at the same mixture proportions. According to EuroSoilStab (2002), the strength of field mixed materials may be 20 to 50 percent of the strength of laboratory mixed specimens. According to CDIT (2002), the strength of field mixed materials may be 20 to 100 percent of the strength of laboratory mixed specimens. The percentage depends on the type and operation of the mixing equipment, as well as the soil type and curing conditions. Consequently, designers should speak with deep mixing contractors during the design phase of a project to estimate the practically achievable relationship between the strength of field mixed and laboratory mixed materials for soil conditions at the project site, as well as the practical range of dose rates that can be applied.

Most strength and stiffness information about deep mixed materials comes from unconfined compression tests. Numerous studies (e.g., Takenaka and Takenaka 1995, Dong et al. 1996, Bruce 2000, CDIT 2002, Matsuo 2002, Miura et al. 2002, EuroSoilStab 2002, Hayashi 2003, Shiells et al. 2003, Filz et al. 2005, Jacobson et al. 2005) show that the unconfined compressive strength of deep mixed materials increases with increasing stabilizer content, increasing mixing efficiency, increasing curing time, increasing curing temperature, decreasing

water content of the mixture, and decreasing organic content of the base soil. One interesting interaction of these factors is that increasing the water content of the mixture can increase mixing efficiency, so that in the case of low-water-content clays, adding water to the mixture can increase the mixture strength (McGinn and O'Rourke 2003). Nevertheless, it remains true that, for thoroughly mixed materials, a decrease in the water-to-cement ratio of the mixture produces an increase in the unconfined compressive strength.

For soils treated by the dry method of deep mixing, values of unconfined compressive strength may range from about 2 to 400 psi, and for soils treated by the wet method of deep mixing, values of the unconfined compressive strength may range from about 20 to 4,000 psi (Japanese Geotechnical Society 2000, Baker 2000, Jacobson et al. 2003). The specified unconfined compression strengths for three recent deep mixing projects in the U.S. are as follows: at the Oakland Airport project, the minimum and average 28-day strengths were specified to be 100 and 150 psi, respectively (Yang et al. 2001); at the I-95/Route 1 interchange project, the minimum and average 28-day strengths were specified to be 100 and 160 psi, respectively (Lambrechts et al. 2003, Shiells et al. 2003); at the Boston Central Artery project, the minimum and maximum 56-day strengths were specified to be 300 and 1000 psi, respectively (Lambrechts et al. 1998, McGinn and O'Rourke 2003).

Stabilized soils tested in triaxial conditions experience a decrease in strength once the strain at peak strength is exceeded (Kivelo 1998). Although soil-cement mixtures are often brittle in unconfined compression tests, the residual strength of soil-cement under even low confining pressures is 65% to 90% of the unconfined compressive strength (Tatsuoka and Kobayashi 1983, CDIT 2002). Kitazume et al. (2000) used a residual compressive strength value equal to 80% of the unconfined compressive strength in limit equilibrium analyses of their centrifuge test results. The residual strength of deep-mixed materials can be used in slope stability analyses to provide safety against progressive failure effects.

There are differences of opinion regarding the most appropriate strength envelope for deep mixed materials for use in stability analyses of column-supported embankments. Masaaki Terashi (personal communication) indicated that the state of practice in Japan is to use a total stress,  $\phi = 0$  and  $c = \frac{1}{2} q_u$  envelope for deep-mixed material. Broms (2003) mentions use of total stress friction angles in the range of 25 to 30 degrees for deep-mixed materials. EuroSoilStab (2002) and Calsten and Ekstrom (1997) utilize a drained, effective stress friction angle of 30 degrees with a range of values for the cohesion intercept depending on the location of the failure surface. EuroSoilStab (2002) states that, for the dry methods of deep mixing, columns should not be used to resist tensile stresses. Brandl (1981), Takenaka and Takenaka (1995), Kivelo (1998), and CDIT (2002) report that the tensile strength of soil improved by the wet method is 10% to 20% of the unconfined compressive strength. Kitazume et al. (1996) report that a value of 15% is used in Japan with wet mix methods.

Variability of the unconfined compressive strength can be expressed in terms of the coefficient of variation, which is the standard deviation divided by the mean. Values of the coefficient of variation in the published literature for deep mixed materials range from about 0.15 to 0.75 (Kawasaki et al. 1981, Honjo 1982, Takenaka and Takenaka 1995, Unami and Shima 1996, Matsuo 2002, Larsson 2005).

Secant values of Young's modulus of elasticity at 50% of the unconfined compressive strength,  $E_{50}$ , have been related to the unconfined compressive strength,  $q_u$ . For the dry method of deep mixing, values of the ratio of  $E_{50}$  to  $q_u$  have been reported in the range from 50 to 250 (Baker 2000, Broms 2003, Jacobson et al. 2005). For the wet method of deep mixing, values of the ratio of  $E_{50}$  to  $q_u$  have been reported in the range from 75 to 1000 (Ou et al. 1996).

Deep mixed materials exhibit non-linear stress-strain response, with higher stiffness at low strains (Tatsuoka et al. 1996, McGinn and O'Rourke 2003). Tatsuoka et al. (1996) point out that local displacement measurements taken directly on specimens can produce higher values of modulus than when displacements are based on relative movement of end platens.

Reported values of Poisson's ratio for deep-mixed material range from 0.25 to 0.50 (CDIT 2002, McGinn and O'Rourke 2003, Terashi 2003, Porbaha et al. 2005).

In many cases, the unit weights of soils treated by deep mixing are not greatly affected by the treatment process. For the dry method of deep mixing, Broms (2003) reports that the unit weight of stabilized organic soil with high initial water content can be greater than the unit weight of untreated soil and that the unit weights of inorganic soils are often reduced by dry mix stabilization. The Japanese CDIT (2002) reports that the total unit weight of the dry-mixed soil increases by about 3% to 15% above the unit weight of the untreated soil. CDM (1985) indicates that, for soils treated by the wet method of deep mixing, the change in unit weight is negligible. David Yang (personal communication) indicated that the unit weight of soil treated by the wet method is often lower than the unit weight of the untreated soil. At the Boston Central Artery/Tunnel Project, McGinn and O'Rourke (2003) report that a significant decrease in unit weight occurred because the initial unit weight of the clay was relatively high and water was added to pre-condition the clay before mixing with cement-water slurry.

### **Analysis Methods for Stability of Column-Supported Embankments**

Stability analysis procedures for embankments supported on piles are presented in BS8006 (1995). Stability analysis procedures for embankments supported on stone columns are presented by Aboshi et al. (1979), Barksdale and Bachus (1983), and Goughnour (1991). Summaries of these procedures are presented in Appendices A and B.

The current state of practice for analysis of the stability of embankments supported on columns installed by the deep mixing method is to use limit equilibrium slope stability analyses with a composite strength of the foundation (CDIT 2002, EuroSoilStab 2002). The composite strength is based on the strength of the unimproved ground, the strength of the deep mixed columns, and the area replacement ratio.

In Japanese practice (CDIT 2002), the strength of the soil between deep mixed columns is reduced to account for strain incompatibility between columns and the untreated soft soil because deep mixed materials typically reach peak strength at relatively small strains, whereas soft soils typically reach peak strength at larger strains. Slip circle analyses are performed to calculate the factor of safety against failure. CDIT (2002) also recommends that separate sliding

stability and bearing capacity analyses should be performed. Furthermore, CDIT (2002) mentions use of finite element analyses to investigate lateral displacements.

In Scandinavian practice (EuroSoilStab 2002, Kivelo 1998, Carlsten and Ekstrom 1995), limit equilibrium slip circle analyses of slope stability are also performed using the composite strength of the improved ground, but the full strength of the unimproved ground is used and the column strengths are limited. The limitations on column strength depend on the factor of safety of the embankment on the unimproved foundation, the location of sliding relative to the embankment side slope, and whether or not columns are overlapped in the form of panels. The Scandinavian procedures are described in detail by Navin (2005).

Broms (1972) described several failure mechanisms, which are shown in Figure 2, for piles used to stabilize slopes. Subsequently, Kivelo (1998), Kivelo and Broms (1999), and Terashi (2005) applied these concepts to deep mixed columns. Failure modes A, B, and C in Figure 2 represent column bending, D represents flow of soil around the column, E represents column tilting, F represents column translation, G represents shearing through the column, and H represents column crushing. Kivelo and Broms (1999) developed expressions for the equivalent shear resistance for each of the failure modes in Figure 2. In several cases, the shear resistance varies with depth along the column and with position beneath the embankment. Thus, implementing this approach would require determining the minimum shear resistance from the eight failure modes shown in Figure 2 at every depth and position beneath the embankment so that a search for the critical failure surface could be made. In addition, there is uncertainty about the accuracy of the equivalent shear resistance calculations. Porbaha (2000) indicates that the approach of Kivelo and Broms (1999) is not used in practice owing to incomplete understanding of the phenomena.

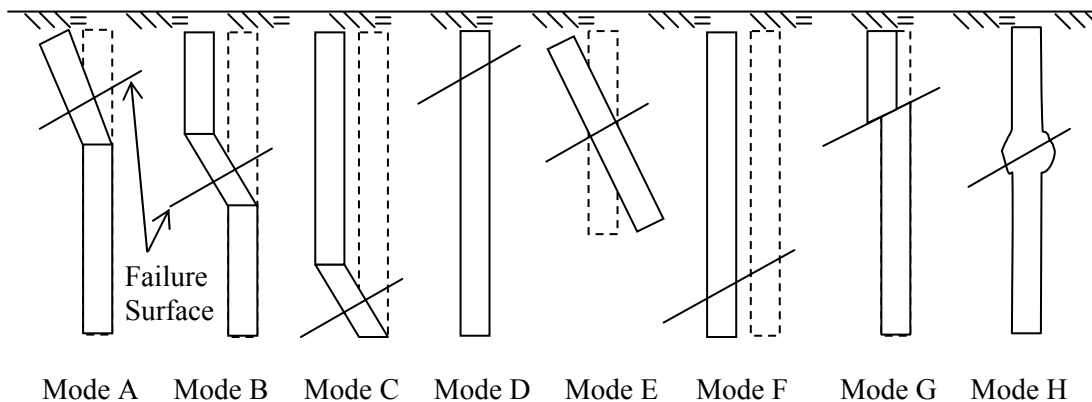


Figure 2. Failure mechanisms for DMM columns (after Kivelo and Broms 1999)

Numerical, stress-strain analyses have been used to evaluate stability of embankments founded on deep-mixed columns (Han et al. 2005, Huang et al. 2006, Navin 2005, Navin and Filz 2006a,c). In addition to shear failure, numerical analyses capture failure mechanisms not included in limit equilibrium slope stability analyses. Allowing other failure mechanisms, such as column bending and tilting, results in lower and more realistic values of factor of safety than when shear failure is the only failure mechanism permitted.

## **Results of Data Collection and Statistical Analyses of Deep-Mixed Material Strength and Stiffness**

This section summarizes the results of data collection and statistical analyses of the strength and stiffness of material created by the deep mixing method at nine project sites in the U.S. Additional details are available in Navin and Filz (2006b) and Navin (2005).

Based on differences in construction technique, subsurface conditions, and sampling technique, the unconfined compressive strength test data from these nine projects were organized into 13 data sets. Table 1 provides the basic statistics for each data set such as the number of samples, mean value, standard deviation, and coefficient of variation, which is the standard deviation divided by the mean. The values of coefficient of variation based on the raw strength data range from 0.34 to 0.79, and the average value for all 13 data sets is 0.57.

Regression analyses were performed to investigate which measured parameters have a significant influence on mixture strength. Although the correlations were not especially strong, it was found that specimen age and water-to-cement ratio of the slurry for wet deep mixing do have a significant impact on strength. Because these parameters can be controlled or accounted for in design, the variation in strength due to these trends is not part of the inherent variability of the mixed material. The variation in strength due to variation in specimen age and water-to-cement ratio of the slurry was removed, and the resulting adjusted values of coefficient of variation are also listed in Table 1. These adjusted values of coefficient of variation range from 0.17 to 0.67, and the average value for all 13 data sets is 0.39.

Table 1. Unconfined compressive strength of deep-mixed material from nine projects

Source <sup>a</sup>	Project	Sample Type	No. of Tests	Strength			
				Mean (psi)	$\sigma$ (psi)	Raw <sup>b</sup> $V$	Adjusted <sup>c</sup> $V$
Weatherby, D.	Baker Library	Wet Grab	81	209	95.7	0.459	0.174
	Capitol Visitor Center	Wet Grab	44	147	72.5	0.494	0.168
	Knafel Center	Wet Grab	106	226	118	0.522	0.199
	Total		231	204	107	0.520	0.209
Yang, D.	Port of Oakland	Core	118	433	225	0.521	0.524
	Oakland Airport	Core	184	513	228	0.445	0.443
	Total		302	464	229	0.494	0.496
Dasenbrock, D.	Glen Road Interchange Ramps G&F	Core	184	473	162	0.343	0.265
	Glen Road Interchange Ramps H&E	Core	634	412	175	0.425	0.223
	Total		818	426	180	0.421	0.330
Burke, G.	Blue Circle / Kinder Morgan Cement Silos	Wet Grab	487	682	506	0.742	0.589
Farrar, J.	Jackson Lake Dam - Owner Samples	Core	355	673	453	0.673	0.608
	Jackson Lake Dam - Contractor Samples	Wet Grab	1710	404	261	0.645	0.246
	Jackson Lake Dam - Owner Samples	Wet Grab	1018	333	263	0.789	0.255
	Total		2569	444	299	0.746	0.386
Shiells, D.	I-95 Interchange - Single Auger	Core	473	412	276	0.669	0.670
	I-95 Interchange - Multiple Auger	Core	2199	496	329	0.663	0.662
	Total		2672	481	322	0.669	0.668

Notes: <sup>a</sup>All data in this table came from personal communications with these sources in 2004.

<sup>b</sup>The “Raw” values of variance are calculated based on the raw strength data.

<sup>c</sup>The “Adjusted” values of variance are calculated after removing the influences of sample age and water-to-cement ratio of the slurry.

Goodness-of-fit tests established that the lognormal distribution provided the best fit to the data sets. As an example, the quality of fit for one of the data sets is presented in Figure 3. The results of the goodness-of-fit tests for all the data sets are presented in Navin and Filz (2006b).



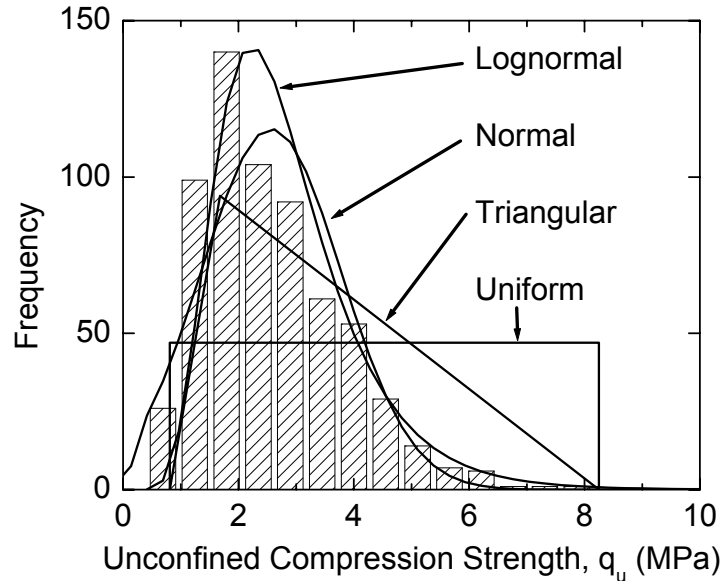


Figure 3. Comparisons of the fit between the data from Glen Road Interchange Ramps E & H and four standard distributions

Sufficient data existed to evaluate spatial correlation and the autocorrelation distance for the strength of material created by the wet method of deep mixing at three project sites: the I-95/Route 1 interchange, the Oakland Airport, and the Glen Road Interchange Ramps E & H. The resulting values of autocorrelation distance ranged from 40 to 60 feet. In reliability analyses, strengths within the autocorrelation distance are assumed to be completely correlated, and strengths beyond the autocorrelation distance are assumed to be completely uncorrelated.

Based on over 2,000 data points from the I-95/Route 1 project, the ratio of modulus to unconfined compressive strength,  $E_{50}/q_u$ , is about 300 for soil-cement columns created using the wet method of deep mixing with either single or multiple augers. This ratio applies after removing extreme values of  $E_{50}$  from the data set. There is considerable scatter in the data, but analyses showed that the value of coefficient of variation for  $E_{50}$  is about the same as the value of coefficient of variation for  $q_u$  after extreme values of  $E_{50}$  are removed from the data set. If the extreme values of  $E_{50}$  are left in the data set, the values of  $E_{50}/q_u$  and coefficient of variation of  $E_{50}$  are higher. The details are presented in Navin and Filz (2006b).

### Results of Verification Studies for the Numerical Stress-Strain Analyses

Because numerical analyses are sensitive to material modeling and numerical modeling issues, it is important that verification analyses be performed. It is also important that principles of mechanics be followed to avoid getting the right answers for the wrong reasons. In this research, numerical analyses of the I-95/Route 1 test embankment and published centrifugal model studies were performed to verify suitability of the analysis methods employed.

The I-95/Route 1 test embankment is a well instrumented case of an embankment founded on columns installed by the dry method of deep mixing. The dry mix columns were 2.66 ft in diameter and installed in a triangular pattern at center-to-center spacings of 6 and 10 ft

in two different regions beneath the embankment to produce area replacement ratios of 17.9% and 6.4%, respectively. The embankment was 18 ft high, and it was constructed with crushed aggregate after an initial placement of approximately 3 ft of bank run sand and gravel. One side of the test embankment consisted of a geosynthetic-reinforced retaining wall, and the other sides of the test embankment were constructed at 2H:1V slopes. Instrumentation included settlement plates, settlement pins, a ground water observation well, vertical inclinometers, a horizontal inclinometer, vibrating-wire piezometers, magnetic extensometers, pressure cells, and thermistors. The test embankment, as well as the material and numerical modeling details, is fully described in Stewart et al. (2004) and Navin (2005).

The results of undrained, plane strain FLAC analyses of the I-95/Route 1 test embankment are compared with readings from a vertical inclinometer installed at the toe of the geosynthetic-reinforced wall in Figure 4. It can be seen that the agreement between measured and calculated response is good.

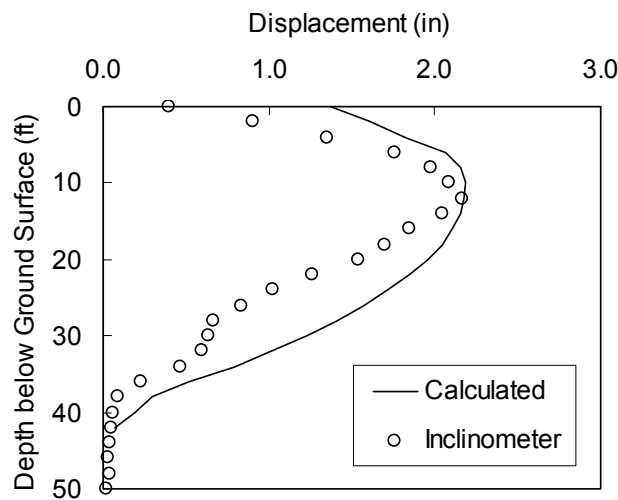


Figure 4. Measured and calculated response of the I-95/Route 1 test embankment

In addition to the lateral deformation analyses for the I-95/Route 1 test embankment, analyses for lateral deformations and slope stability failure modes of column-supported embankments and structures were also verified against the centrifuge model tests of Kitazume et al. (1996) and Inagaki et al. (2002). Details of the centrifugal model tests, as well as the material and numerical modeling procedures for the numerical analyses, are described in Navin (2005), and the results are summarized here.

The centrifuge model tests performed by Kitazume et al. (1996) involved a caisson subject to several combinations of vertical and horizontal load application. The caisson was founded on soft clay improved with soil-cement columns using a range of column strengths for the series of tests. Kitazume et al. (2000) performed numerical analyses that were in good agreement with the centrifuge test results. Undrained plane strain analyses performed by Navin (2005) using FLAC with dimensions and material property values as presented by Kitazume et al. (1996, 2000) were also in good agreement with the centrifuge test results, as shown in the load versus deflection curve in Figure 5. An important feature of the FLAC analyses is that they

successfully captured column bending failure that occurred in the centrifuge model tests for cases with low column strength, as shown by the analysis results in Figure 6.

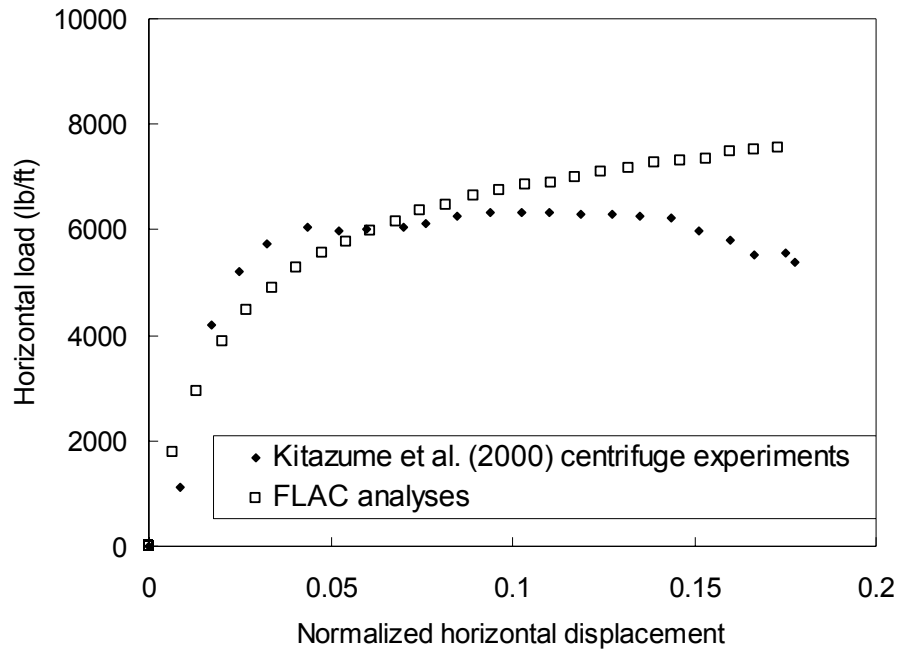


Figure 5. Calculated versus measured deflections for Kitazume et al. (1996) centrifuge tests

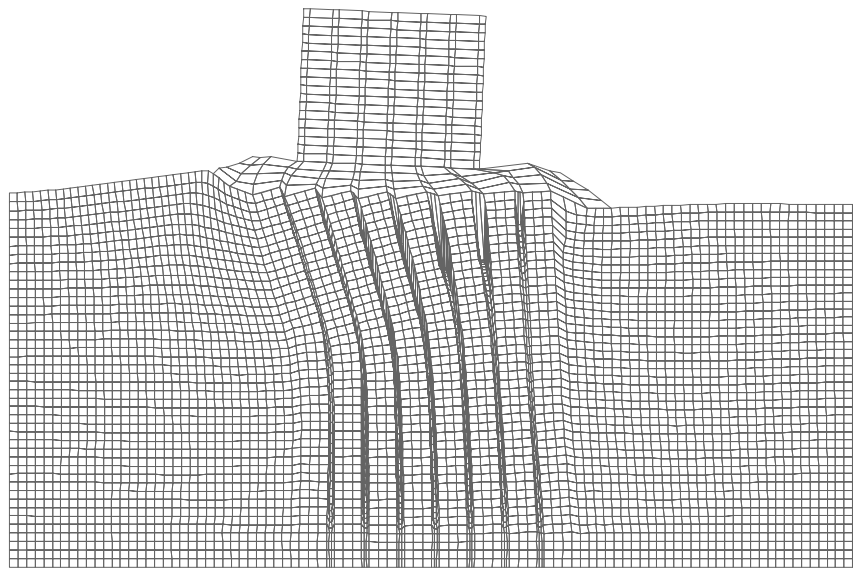


Figure 6. Deformed mesh showing column bending failure in analyses of the Kitazume et al. (1996) centrifuge tests

The centrifuge model tests performed by Inagaki et al. (2002) involved an embankment founded on soft clay that had been improved with several rows of isolated soil-cement columns. Inagaki et al. (2002) performed numerical analyses that matched the deformations measured in each row of columns in the centrifuge tests. Water-soil coupled, plane strain analyses performed by Navin (2005) using FLAC with the property values described by Inagaki et al. (2002)

matched the measured deflections. In addition, undrained total-stress plane strain analyses were performed using FLAC and FLAC3D. The FLAC and FLAC3D results were in good agreement with the centrifuge test results, as shown by the column deflections in Figure 7.

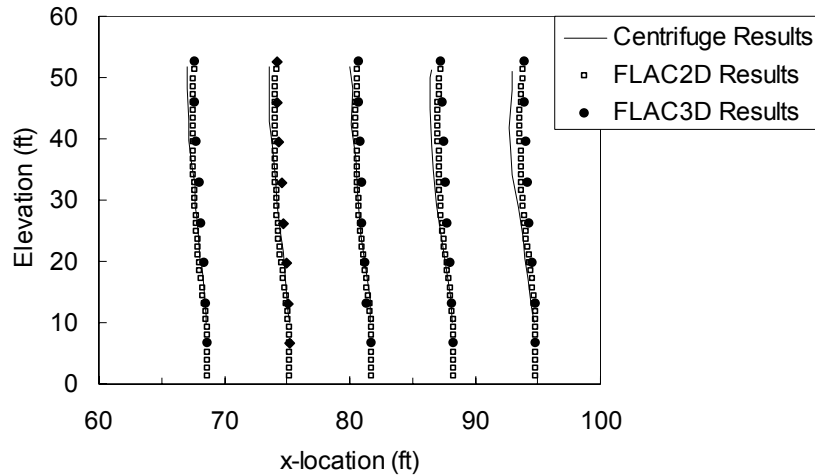


Figure 7. Calculated versus measured deflections for the Inagaki et al. (2002) centrifuge tests

An important question related to two-dimensional analyses of an embankment supported on isolated columns is the width of the strips used to represent the columns. All of the two-dimensional FLAC results shown above used widths selected to produce the same area replacement ratio that exists in the three-dimensional geometry. The column modulus was not adjusted. In this approach, the axial stiffness of the columns is the same in two- and three-dimensional representations, but the bending stiffness of the columns is underestimated in the two-dimensional representation. Nevertheless, this approach to two-dimensional analyses produces good agreement with the lateral deflections from field case histories, centrifuge model tests, and three-dimensional analyses. One factor that contributes to this outcome is that the shear stiffness of the ground between columns and beyond the toe of the embankment has an important influence on lateral deflections, and this reduces the impact of variations in the bending stiffness of the columns. This issue is addressed in more detail in Navin and Filz (2006a).

### Results of Reliability Analyses for Stability and Extrusion

This section presents the results of reliability analyses that were performed using numerical stress-strain analyses and limit equilibrium analyses of an example embankment. First, the example embankment is described. Second, the results of limit equilibrium and numerical analyses of slope stability of the example embankment using mean property values are presented. Third, reliability analyses of slope stability based on limit equilibrium and numerical analyses are presented. Fourth, a parameter study on column strength is presented. Fifth, reliability analyses of extrusion are discussed. Finally, reliability concepts are used to develop statistically based specifications for construction of deep-mixed materials. A detailed description of the reliability analysis procedures used in this research is included in Appendix D. Spreadsheets that facilitate computations required for reliability analyses have been provided to VTRC.

## Example Embankment

The example embankment is 18 ft high, as shown in Figure 8. The existing subsurface materials beneath the embankment consist of a two-foot thick layer of sand fill that overlies a 28-ft-thick clay layer that, in turn, overlies ten feet of sand. The ground water table is at the top of the clay layer. Analyses were performed for two arrangements of deep-mixing-method material beneath the embankment. Figure 8 shows isolated columns being used beneath both the side slope and the central, full height portion of the embankment. The columns are 32 feet long, extending from the top of the sand fill, through the clay layer, and two feet into the base sand layer. The columns are three feet in diameter, arranged in a square array with a six-foot center-to-center spacing, as shown in plan view in Figure 9. This results in a replacement ratio of 20%.

The other arrangement considered for analysis employs continuous panels of deep-mixed material beneath the side slopes and isolated columns beneath the full embankment height, as shown in Figures 10 and 11. The panel widths are selected to produce an area replacement ratio of 20% so that comparisons between the cases illustrated in Figures 8 and 10 can be made directly.

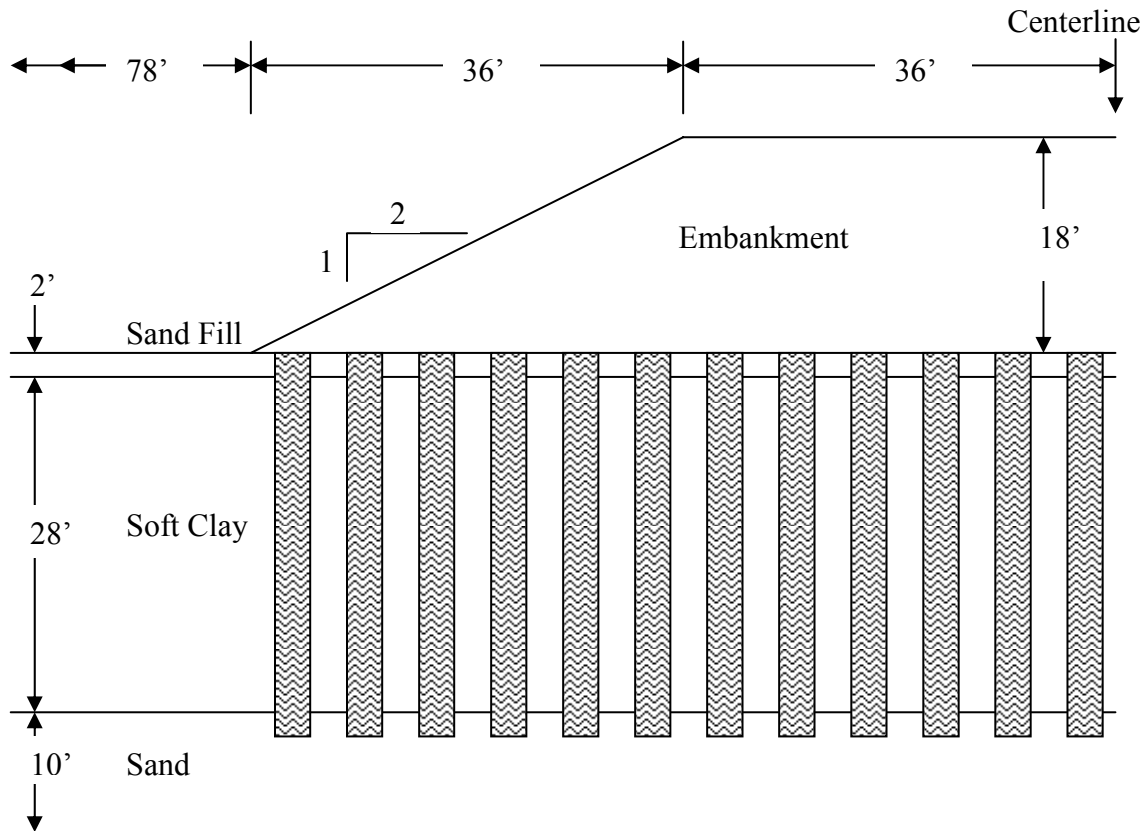


Figure 8. Profile view of the example embankment with isolated columns everywhere

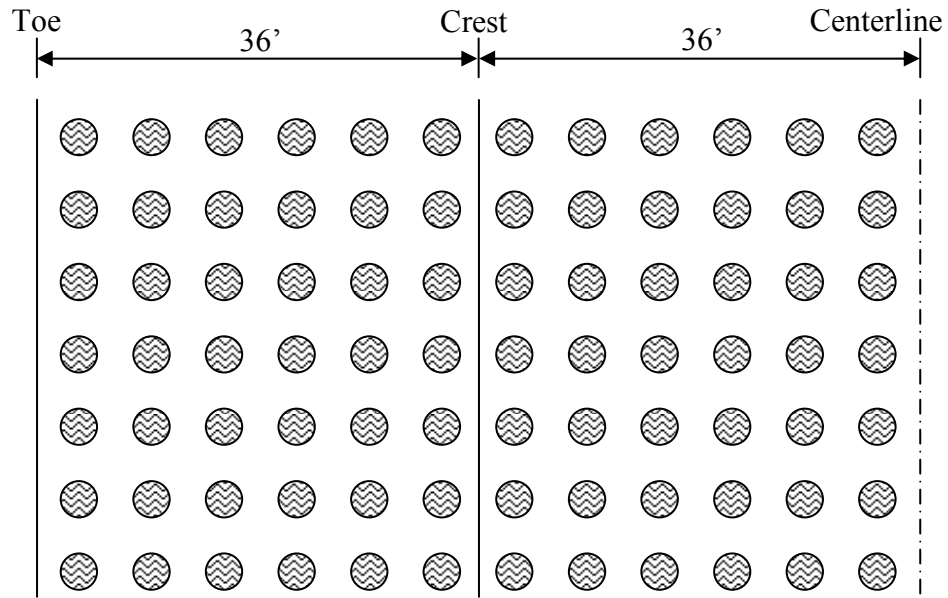


Figure 9. Plan view of the example embankment with isolated columns everywhere

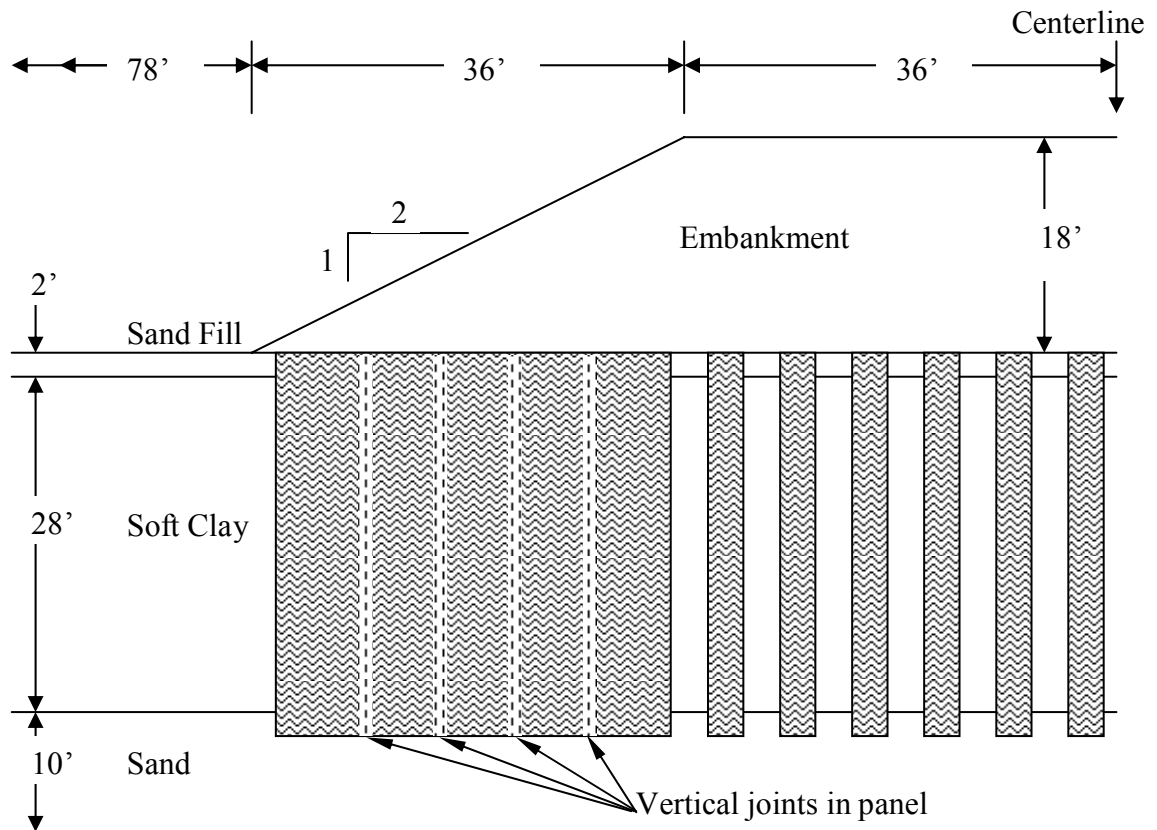


Figure 10. Profile view of example embankment with continuous panels under side slopes

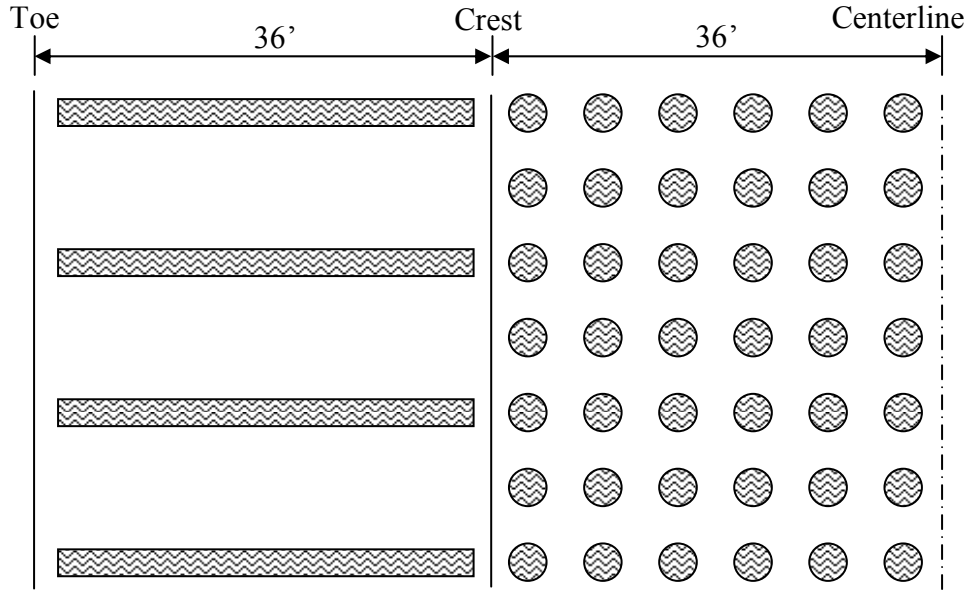


Figure 11. Plan view of the example embankment with continuous panels under side slopes

Mean values of the material properties are listed in Table 2. The clay is assumed to be lightly overconsolidated, with the preconsolidation pressure equal to 700 psf plus the initial effective vertical stress. The undrained shear strength of the clay,  $s_u$ , is assumed to vary with preconsolidation pressure according to the relationship  $s_u/p_p = 0.23$ , where  $p_p$  is the effective preconsolidation pressure. Thus, the value of  $s_u$  is 214 psf at the top of the clay and 430 psf at the bottom of the clay layer. The average shear strength of the clay is 322 psf. The Young's modulus of the clay is set equal to 200 times its undrained shear strength. For short-term loading, the columns are characterized as having a cohesion intercept of 100 psi and a total stress friction angle of zero. Initial lateral stresses in the clay layer were computed based on effective stress values of the lateral earth pressure coefficient,  $K_0$ , which were determined based on a drained friction angle of  $28^\circ$  and the applicable values of overconsolidation ratio as a function of depth using the procedures described in Appendix C. The hydrostatic pore water pressures were added to the effective lateral stresses to obtain the total lateral stresses.

Table 2. Mean material property values used for analysis of the example problem

Material	Unit Weight (pcf)	$E$ (psf)	$\nu$	$c$ (psi)	$\phi$ (deg)
Embankment	125	625,000	0.3	-	35
Sand Fill	115	250,000	0.33	-	30
Clay	96	$200s_u$	0.45	Varies	0
Base Sand	140	1,000,000	0.26	-	40
Columns	96	4,320,000	0.45	100	0

## Limit Equilibrium and Numerical Analyses of Slope Stability

### *Limit Equilibrium Analyses*

Limit equilibrium analyses of the stability of the example embankment were performed using the mean property values listed in Table 2 and discrete representation of the isolated columns, as shown in Figure 12. The columns were represented using 1.2-ft-wide vertical strips at a 6-ft center-to-center spacing to produce an area replacement ratio of 20%. The full strength of the columns and soil, as listed in Table 2, were used in the analyses, which were performed using Bishop's method as implemented in the computer program UTEXAS4 (Wright 1999). A search for the critical slip circle was performed, and the value of the factor of safety,  $FS$ , against instability was found to be 4.4. The critical circle is shown in Figure 12.

Limit equilibrium analyses of the example embankment were repeated using a composite representation, instead of a discrete representation, of the shear strength of the improved ground:

$$c_{ave} = a_s c_{col} + (1 - a_s) c_{soil} \quad (6)$$

where  $c_{ave}$  = the average shear strength of the composite foundation material,  $a_s$  = the area replacement ratio,  $c_{col}$  = the shear strength of the columns, and  $c_{soil}$  = the shear strength of the clay. For the example embankment, the value of  $c_{ave}$  is 2,994 psf at the top of the clay and 3,168 psf at the bottom.

The composite foundation for limit equilibrium analyses is shown in Figure 13. The composite representation is the same whether isolated columns are used under the side slopes, as shown in Figures 8 and 9, or continuous panels are used under the side slopes, as shown in Figures 10 and 11. In both cases, the area replacement ratio is the same, and the value of  $c_{ave}$  is the same. Again, the value of the factor of safety was found to be 4.4, and the critical circle is shown in Figure 13.

These results show that limit equilibrium analyses produce high values of factor of safety for the conditions of this example and that they do not distinguish between isolated columns and continuous panels of deep-mixed material beneath the side slopes.



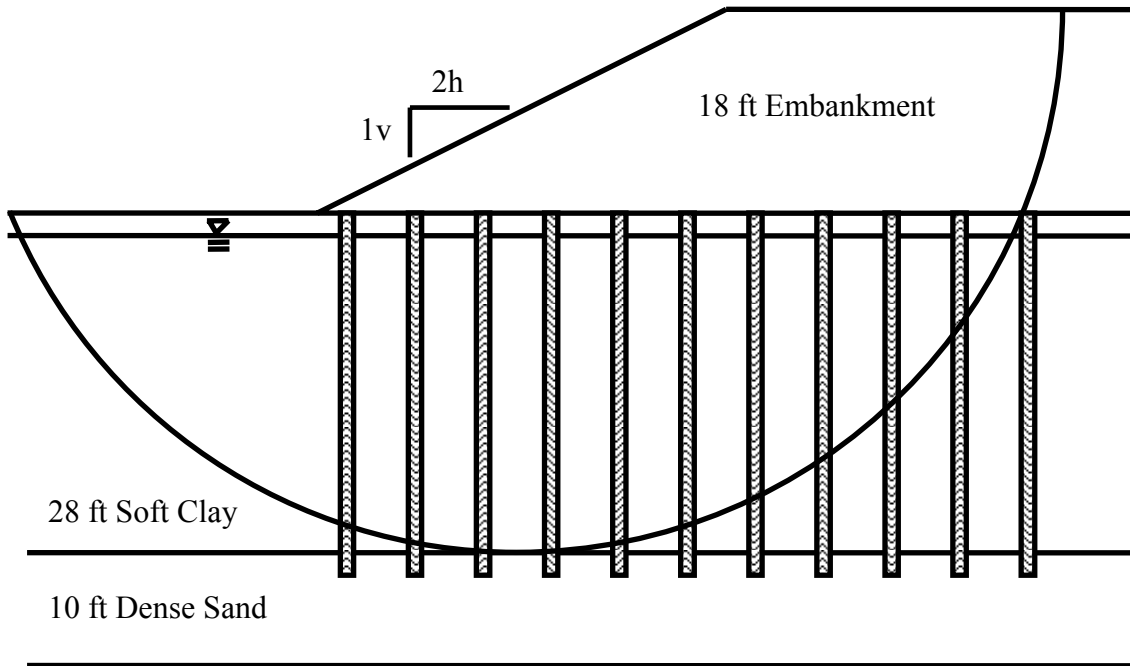


Figure 12. Limit equilibrium slope stability analyses using discrete columns.

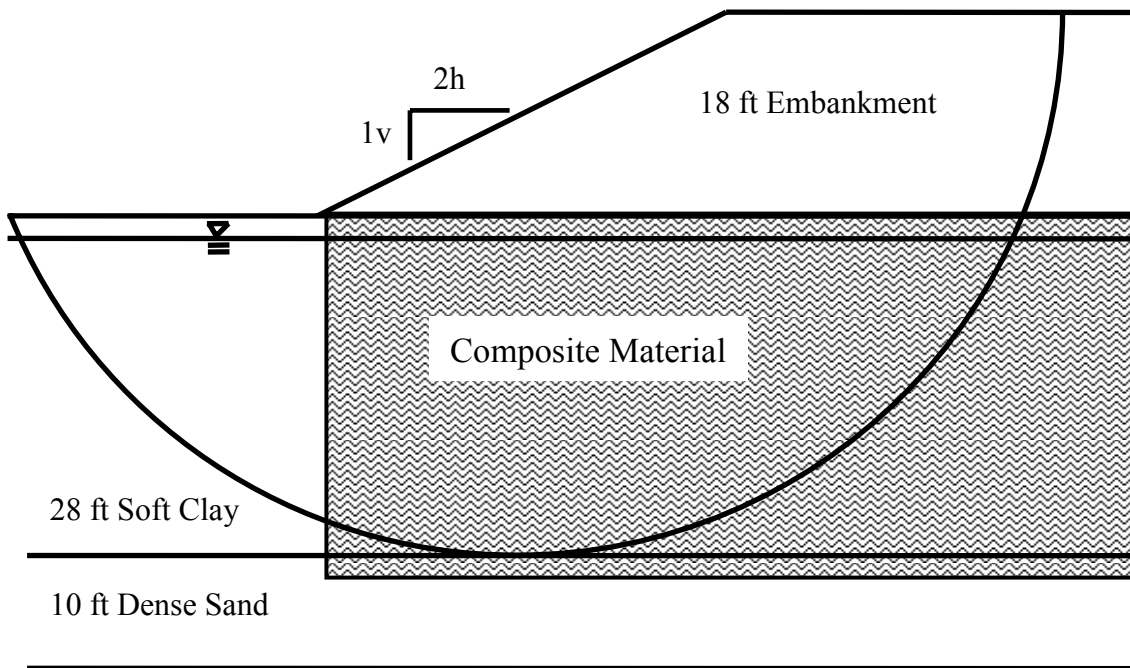


Figure 13. Limit equilibrium slope stability analyses using a composite foundation



















































































































