National Technical University of Athens
School of Civil Engineering
Geotechnical Department – Foundation Engineering Laboratory

A Geotechnical Engineering Seminar Presentation:

Load Transfer, Settlement, and Stability of Embankments Founded on Columns Installed by Deep Mixing Methods

by
George M. Filz

Abstract:
In recent years many projects use deep-soil-mixing columns for the improvement of soft ground. These methods permit accelerated construction of embankments and protect adjacent facilities that might otherwise be damaged by settlements induced by the new embankment load. The design of these methods used to be more art than science. In order to put more science into the art of deep soil mixing a simplified design approach for geosynthetic-reinforced, load-transfer platforms in column-supported embankments has been developed that takes into account the load-deformation response of all the important system components. Stability analysis of embankments founded on deep-mixing-method columns is complicated by the fact that multiple failure mechanisms are possible. Limit equilibrium analyses only reflect composite shearing, which is not the critical failure mode in many cases of practical interest. Numerical analyses can capture a wider range of failure modes, including composite shearing, column bending, and column tilting. An additional complication is that deep-mixed ground is highly variable, and this has a nonlinear impact on reliability analyses for column-supported embankments. Of several approximate reliability analysis methods, the Hasofer-Lind method was found to produce the best determination of reliability compared to direct integration.

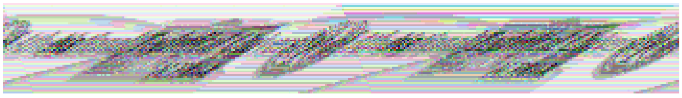
About the Speaker:

Professor Filz obtained bachelor's and master's degrees in civil engineering from Oregon State University, after which he worked in private engineering practice from 1981 through 1988. He obtained his doctor's degree from Virginia Tech in 1992, and has been a faculty member in the Civil and Environmental Engineering Department at Virginia Tech since then. Dr. Filz's main research interests are in soil improvement, foundation engineering, and environmental geotechnics. He has extensive involvement with soil improvement projects in the US and has consulted on numerous important soil improvement projects. He received the Thomas A. Middlebrooks Award in 2003 and the J. James R. Croes Medal in 2006, both from the American Society of Civil Engineers.

Load Transfer, Settlement, and Stability of Embankments Founded on Columns Installed by Deep Mixing Methods

George Filz
Virginia Tech

VirginiaTech



Load Transfer, Settlement, and Stability of Embankments Founded on Deep-Mixing-Method Columns

- Introduction
- Load Transfer and Settlement
- Stability

The Deep Mixing Method (DMM)

- Binders added to soil using rotary mixing tools.
  - Dry method
  - Wet method
- Binder materials can include:
  - Cement
  - Fly ash
  - Ground blast furnace slag
  - Lime
  - Additives

The Deep Mixing Method

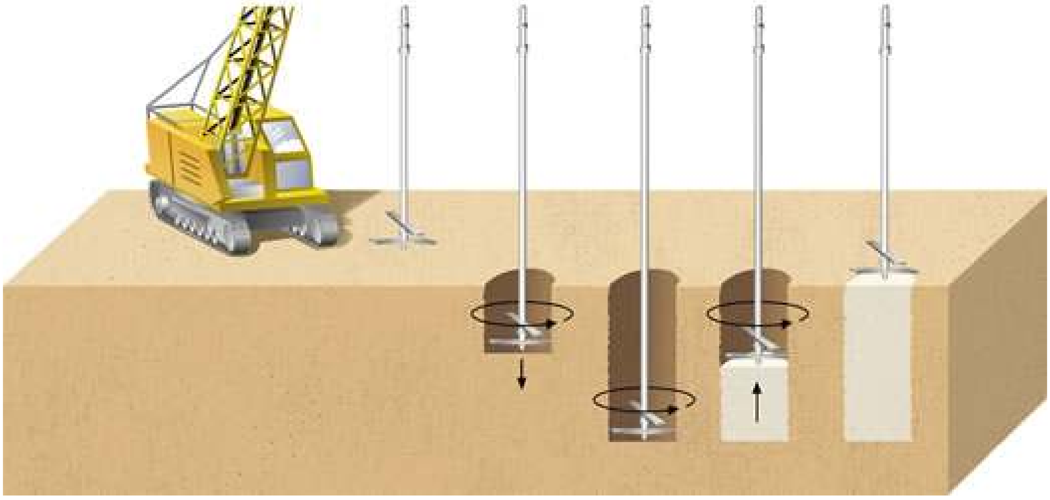


Figure courtesy of Hayward Baker

"Wet" and "Dry" Deep Mixing Methods

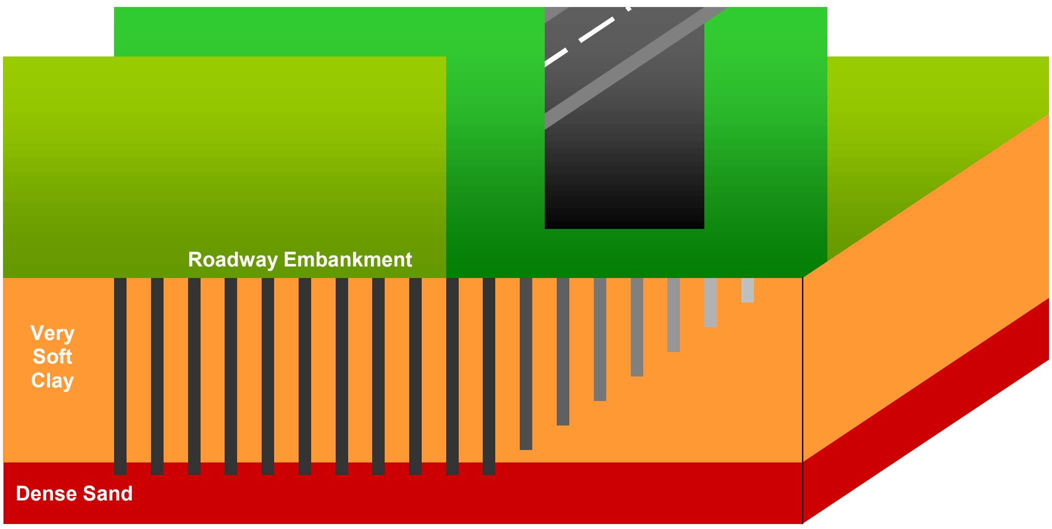
Wet Method:	Dry Method:
Larger & heavier equipment	Smaller & lighter equipment
Used in sands, silts, and clays	Used in soft, wet ground
Significant spoils produced	No significant spoils produced
0.3 m to 3 m diameter	0.3 m to 1 m diameter

Applications: Excavation Support

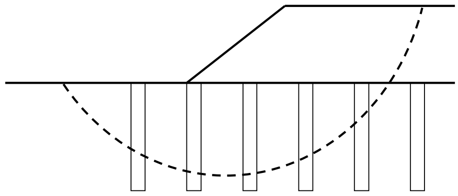
Applications: Bridge Foundation Support

95 m dia. Oil Storage Tanks, Louisiana

Applications:
Column-Supported Embankments



Applications:
Column-Supported Embankments

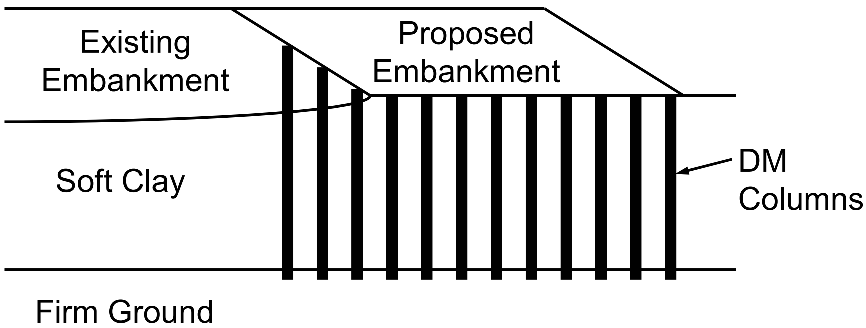


Reasons to use DMM:

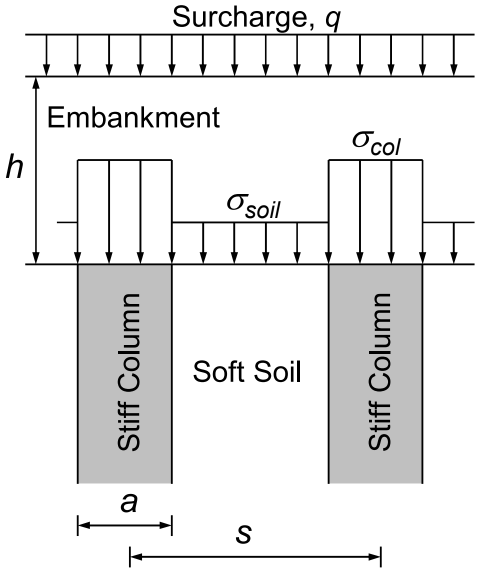
- Schedule constraints: accelerate embankment construction compared to preloading and use of wick drains
- Settlement constraints: prevent settlement of nearby structures
- Stability concerns: provide resistance to deep-seated failure of embankment slopes

Applications:
Widening of Embankments

Protect existing embankment and pavement from settlement induced by new embankment



Load Transfer in Column-Supported Embankments



SRR = Stress Reduction Ratio

$$\sigma_{ave} = \gamma h + q$$

$$SRR = \frac{\sigma_{soil}}{\sigma_{ave}}$$

$SRR = 0 \Rightarrow$ perfect arching

$SRR = 1 \Rightarrow$ no arching

Comparison of Six Methods, Based on Stress Reduction Ratio, *SRR* = $\sigma_{soil}/\sigma_{ave}$

Method	*SRR*					
	a/s = 0.25		*a/s* = 0.33		*a/s* = 0.5	
	h/s = 1.5	*h/s* = 4	*h/s* = 1.5	*h/s* = 4	*h/s* = 1.5	*h/s* = 4
BS8006	0.92	0.34	0.62	0.23	0.09	0.02
Terzaghi	0.60	0.32	0.50	0.23	0.34	0.13
Kempfert et al.	0.55	0.46	0.43	0.34	0.23	0.15
Hewlett&Randolph	0.52	0.48	0.43	0.31	0.30	0.13
Adapted Guido	0.12	0.04	0.10	0.04	0.08	0.03
Carlsson	0.47	0.18	0.42	0.16	0.31	0.12

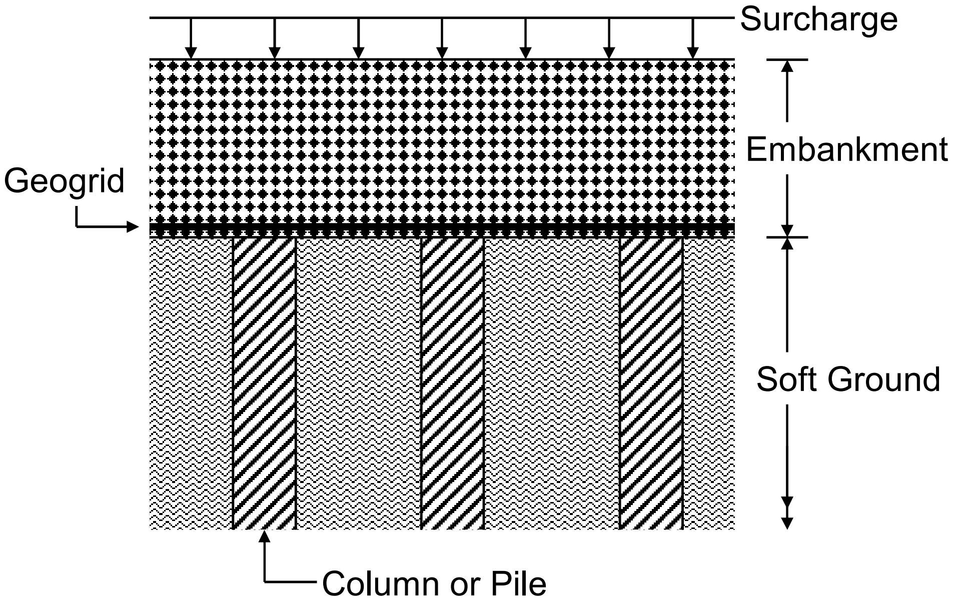
a = pile cap width, *s* = pile cap spacing, *h* = embankment height

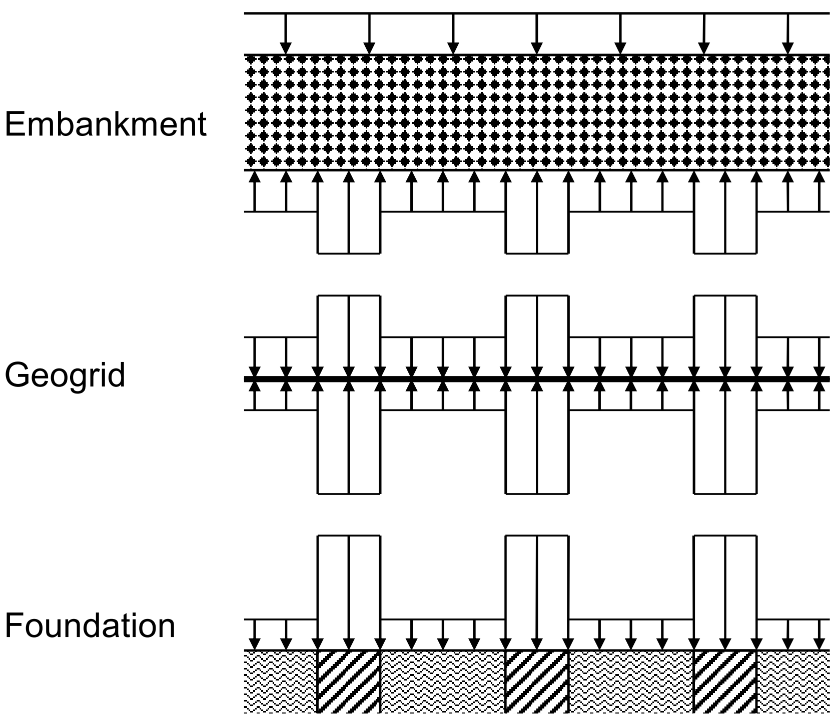
Excessive Deformation and Capacity Failures

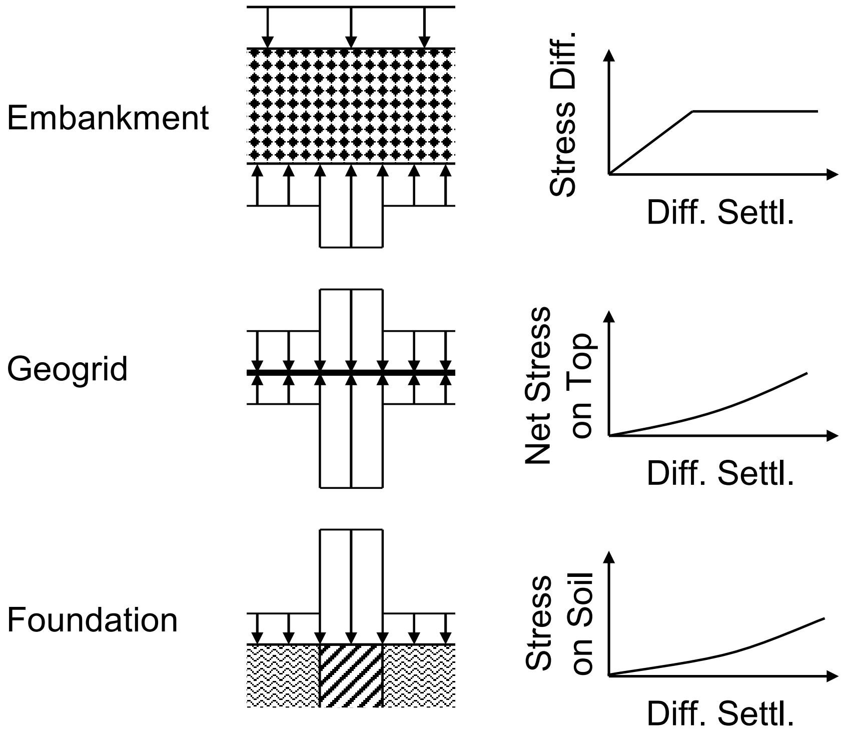
Theory for Stress Reduction Ratio Considering Stiffness of System Components

- Load from embankment
  - Linear elastic solution prior to full strength mobilization, based on differential settlement between column and soil
  - Limiting condition: Terzaghi with $K_T = 0.75$
- Geogrid support included
- Support from soil between columns
  - Upper layers of existing sand allowed
  - Underlying clay layers have nonlinear compressibility (i.e., characterized by Cc, Cr, p_p)
  - Shear between soil and columns
- Column and soil compression calculated over depth to equal settlement
- Can handle driven piles and pile caps
- Automated iterative solution using spreadsheet

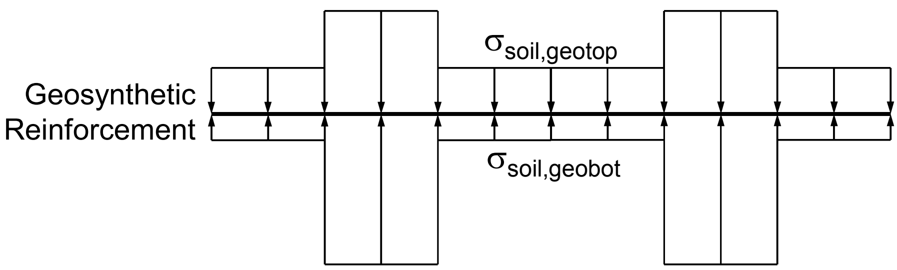
Schematic Diagram of Column-Supported Embankment







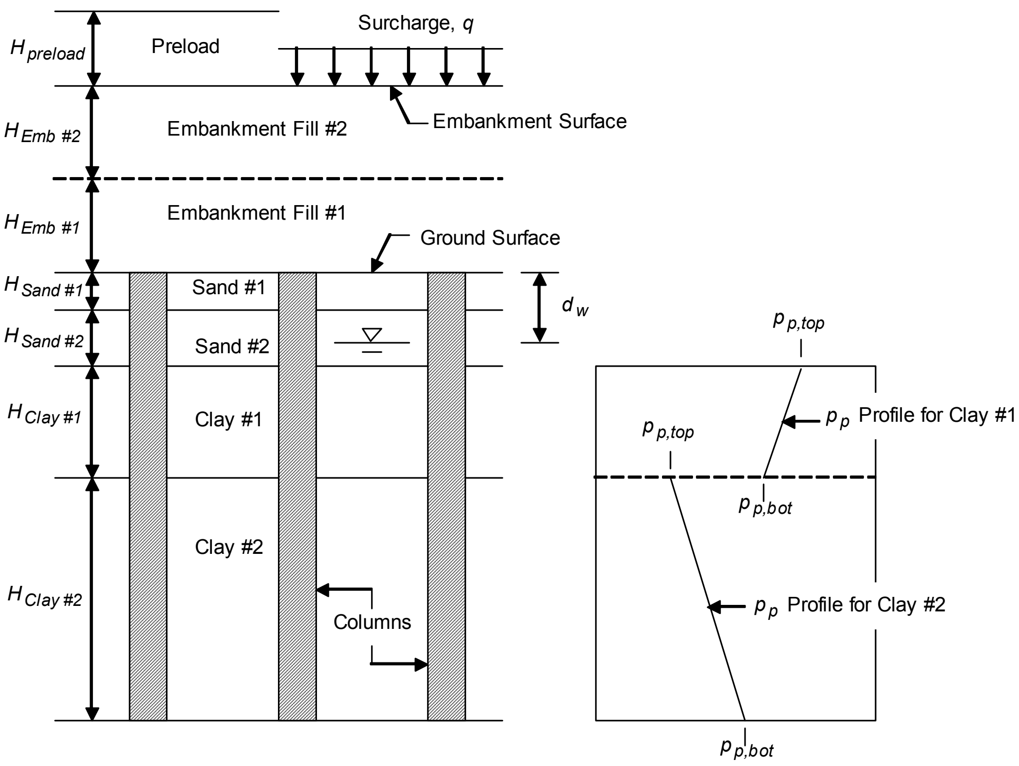
Definition Sketch for SRR_{net}

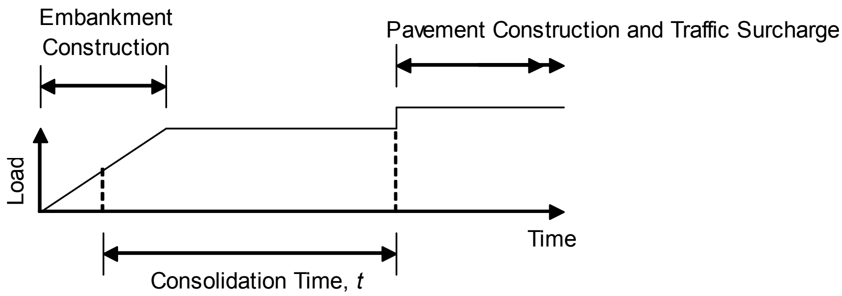


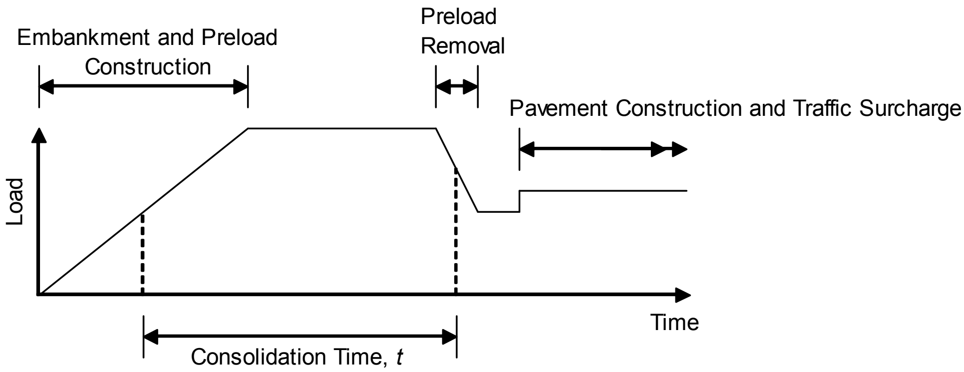
$$SRR_{net} = \frac{\sigma_{soil,geotop} - \sigma_{soil,geobot}}{\gamma H + q} = \frac{\sigma_{soil,geotop} - \sigma_{soil,geobot}}{\sigma_{ave}}$$

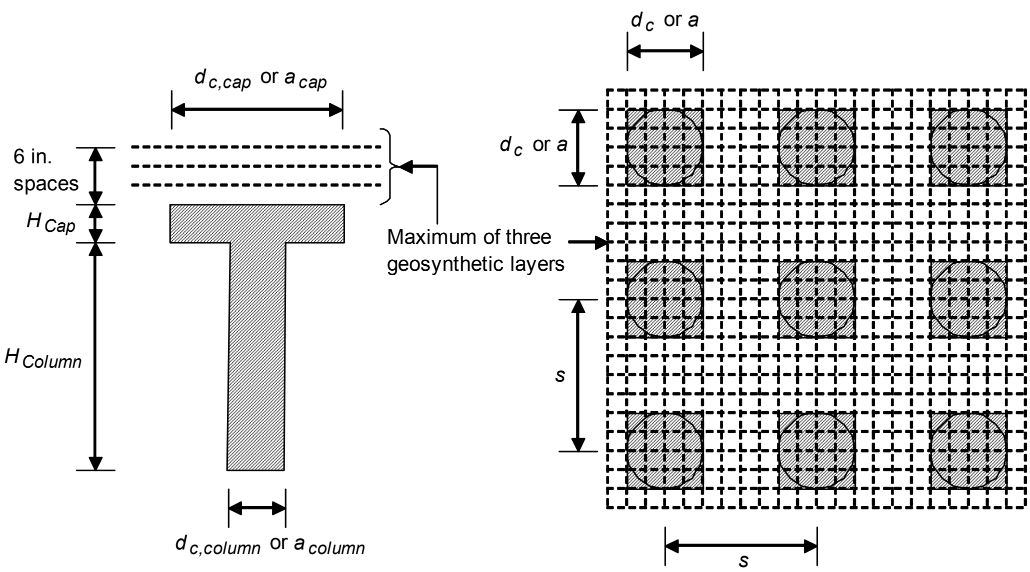
Spreadsheet Solution: GeogridBridge1.1

- Satisfies stress compatibility
- Satisfies displacement compatibility
- Spreadsheet features
  - Multiple soil layers
  - Preloads/Surcharges
  - Piles with pile caps
  - Simple input and output




Embankment
Construction
Pavement Construction and Traffic Surcharge
Load
Time
Consolidation Time, t


Embankment and Preload
Construction
Preload
Removal
Pavement Construction and Traffic Surcharge
Load
Time
Consolidation Time, t


d c,cap or a cap
6 in.
spaces
H Cap
H Column
d c,column or a column
Maximum of three
geosynthetic layers
d c or a
d c or a
s
s

Partial Spreadsheet Input

Geogrid Stiffness, J (lb/ft)	72,000
Long-term, In-Service, Allowable Geogrid Strength S_g (lb/ft)	3,000

	Pile Cap	Column
Vertical Distance from Top to Bottom of Element, H (ft)	2.0	43.0
Column Shape (use R for round and S for square)	S	S
Column Diameter or Width, d_c or a (ft)	4.0	2.0
Young's Modulus, E (psf)	580,000,000	580,000,000
Poisson's Ratio, ν	0.20	0.20
Center-to-center spacing, s (ft)	11.0	

Partial Spreadsheet Output

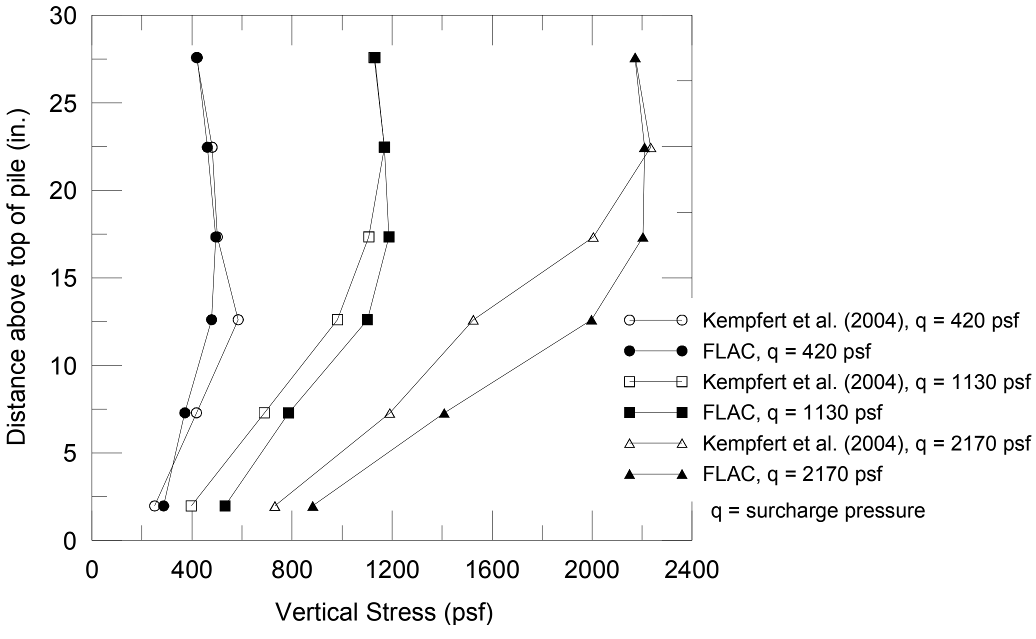
	Value	Criterion
Clear Spacing, $s - a$ (ft)	7.0	≤ 8.0
Area Replacement Ratio at Ground Surface, a_s	0.132	≥ 0.10
Bridging Layer Thickness, $H_{Emb\ \#1}$ (ft)	5.0	≥ 5.0
Geosynthetic Strain, ε_g	0.031	≤ 0.05
Tension in the Geosynthetic Reinforcement, T_g (lb/ft)	2231	≤ 3000.0
Post-Construction Embankment Settlement, S (in.)	2.52	≤ 3.0

Validation of the SRR Theory

Comparisons with

- Pilot-scale tests
- Instrumented case histories
- Numerical analyses

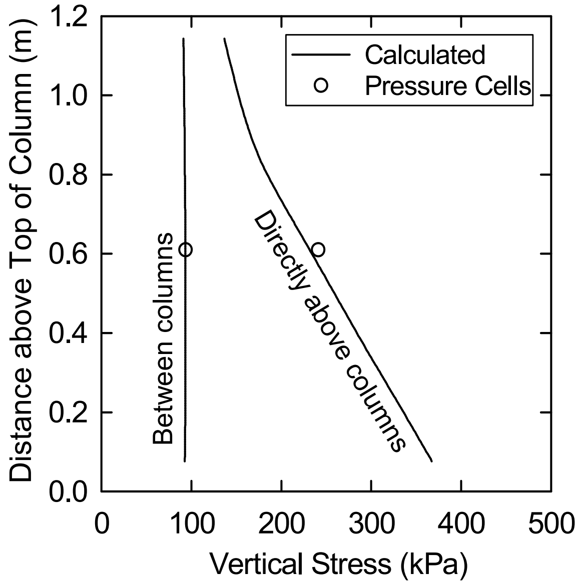
Comparison between Measured and Calculated Pressures in Pilot-Scale Tests



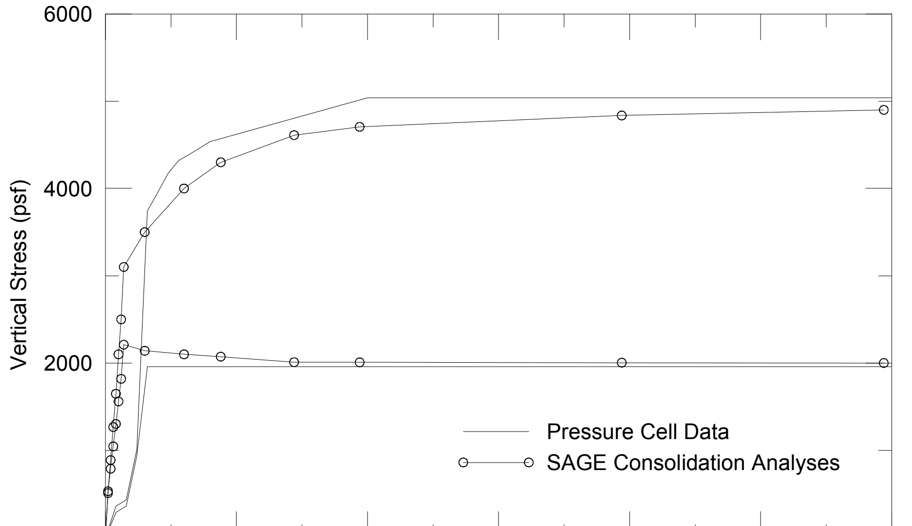
Test Embankment at I-95/Route 1 Interchange

I-95/Route 1 Test Embankment

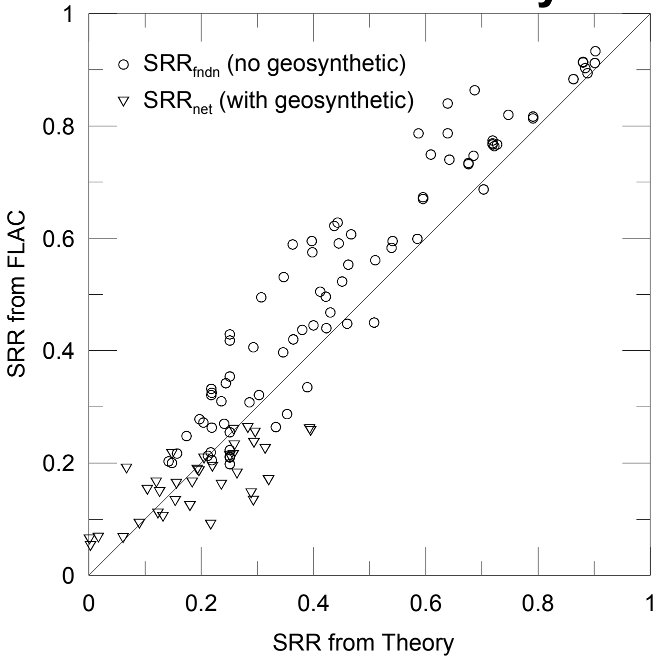
Comparison between Measured and Calculated Pressures at I-95/Route 1 Test Embankment



Comparison between Measured and Calculated Pressures at I-95/Route 1 Test Embankment



Comparison of SRR Values from Theory and Numerical Analyses



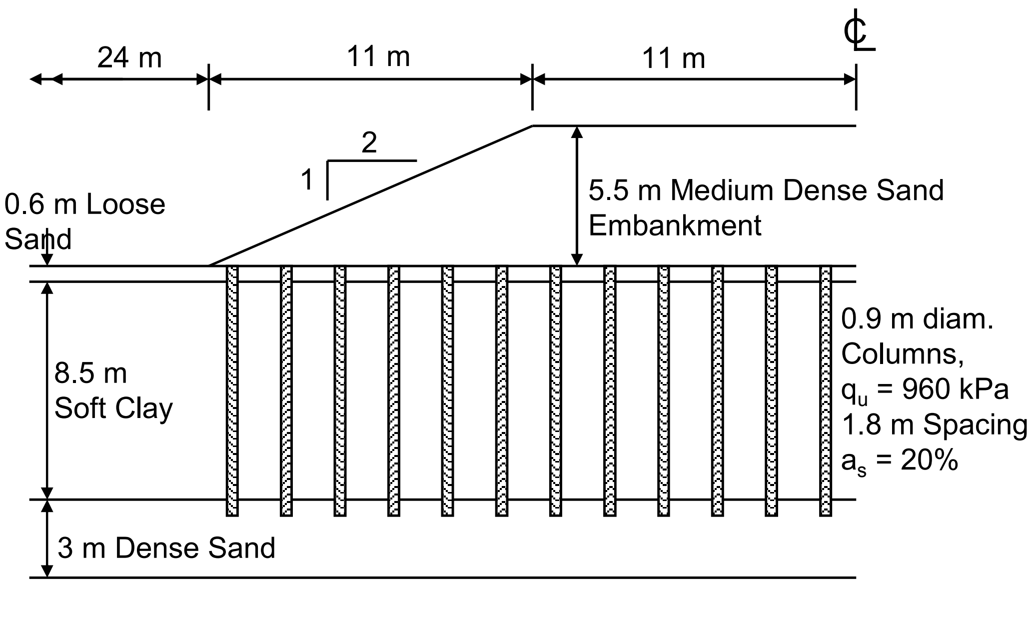
Conclusions: Settlement and Load Transfer

- Previous methods for calculating loads on geosynthetic reinforcement do not consider the stiffness of all system components
- A new theory has been developed that does consider the stiffness of all system components
- The new theory is in good agreement with numerical analyses, pilot-scale tests, and instrumented field case histories
- The new theory has been implemented in an easy-to-use spreadsheet

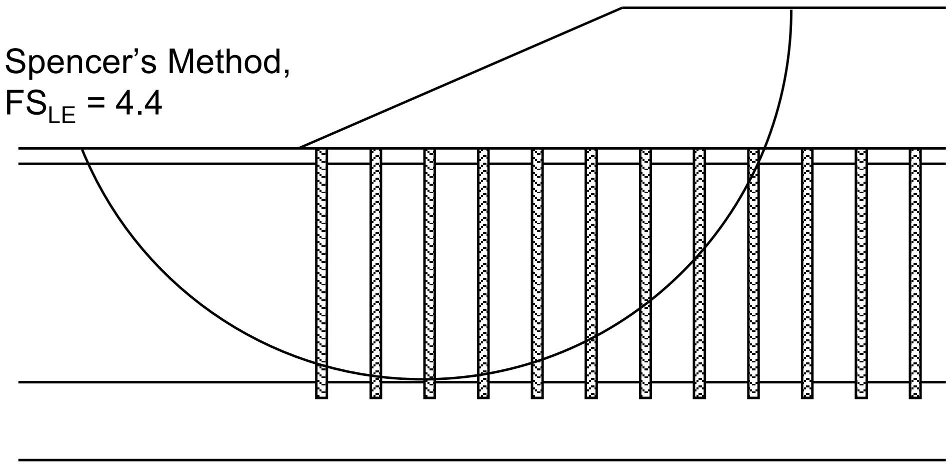
Stability of Column-Supported Embankments

- Limit Equilibrium Analysis
- Numerical Analysis
- Reliability Analysis

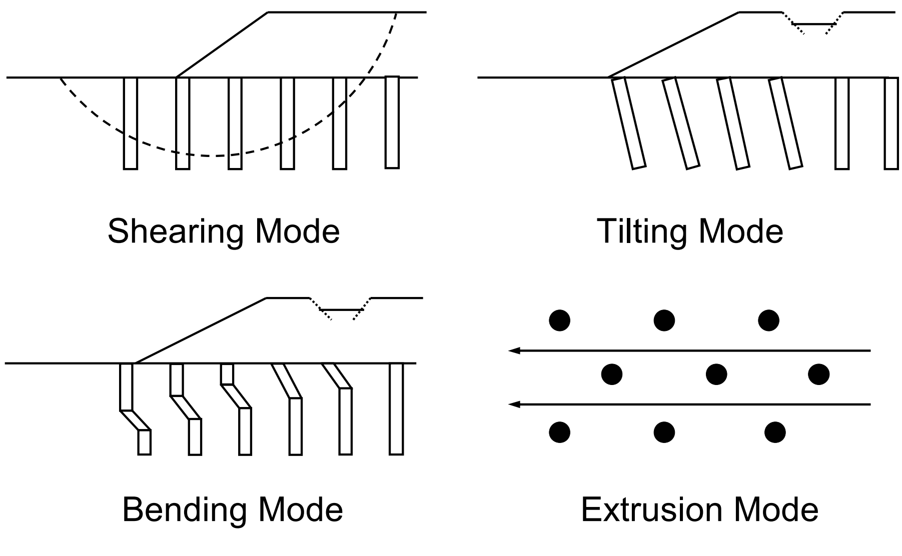
Example Embankment



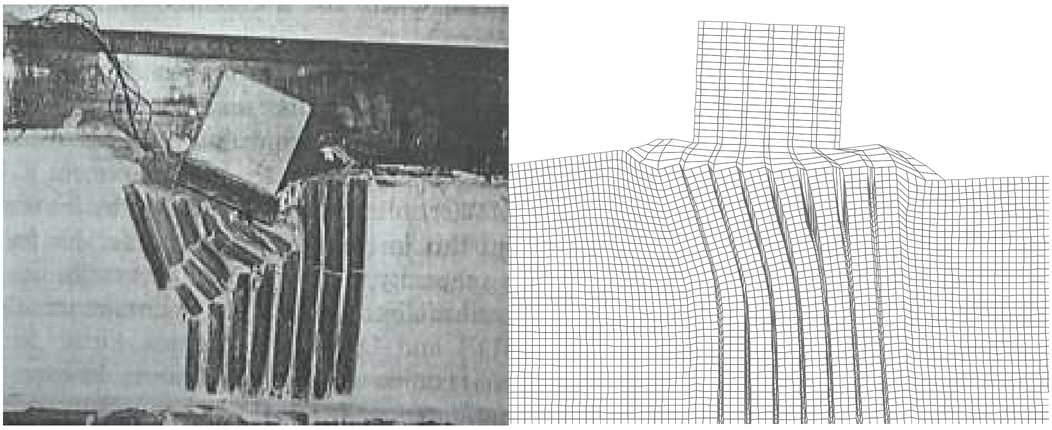
Limit Equilibrium Slope Stability Analysis



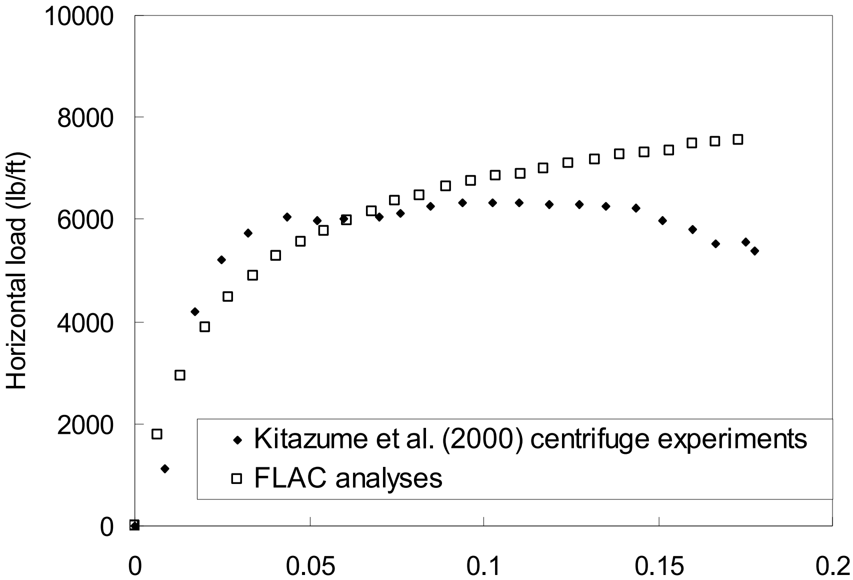
Stability Failure Modes for Embankments Supported on Deep Mixed Columns



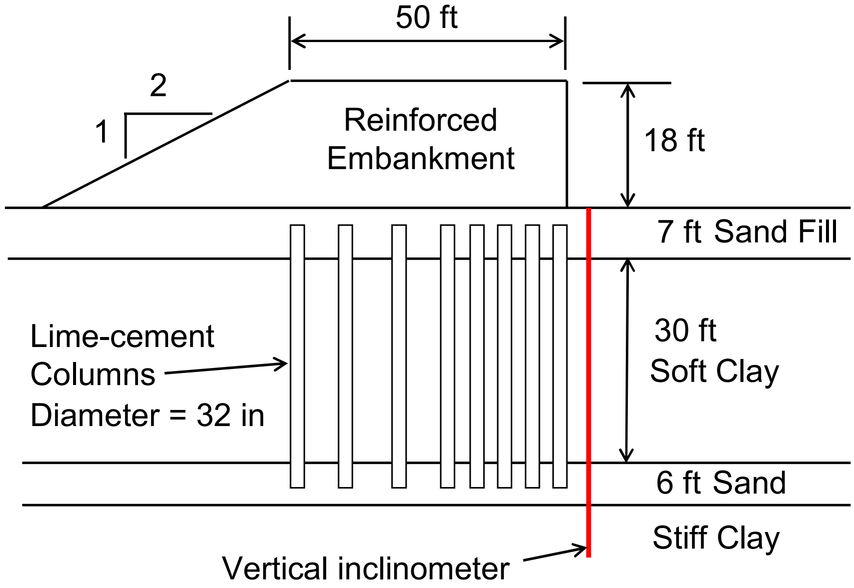
Comparison between Kitazume et al. (1996) Centrifuge Tests and Numerical Analyses



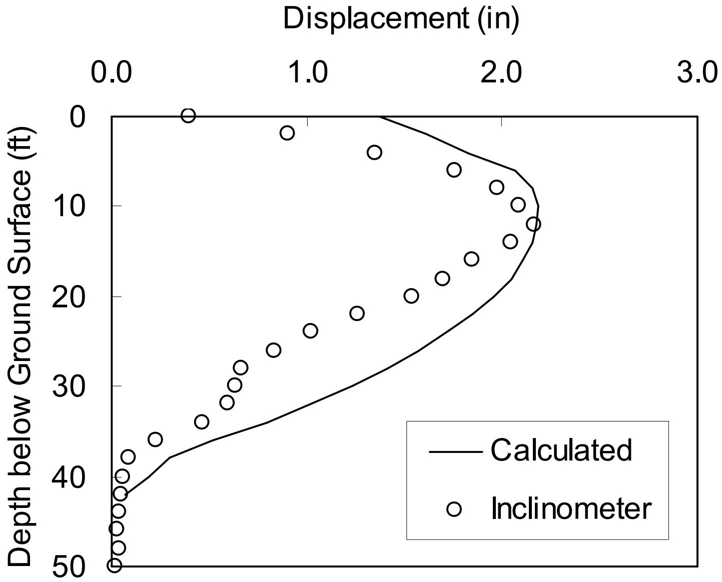
Comparison between Numerical Analyses and Kitazume et al. (1996) Centrifuge Tests



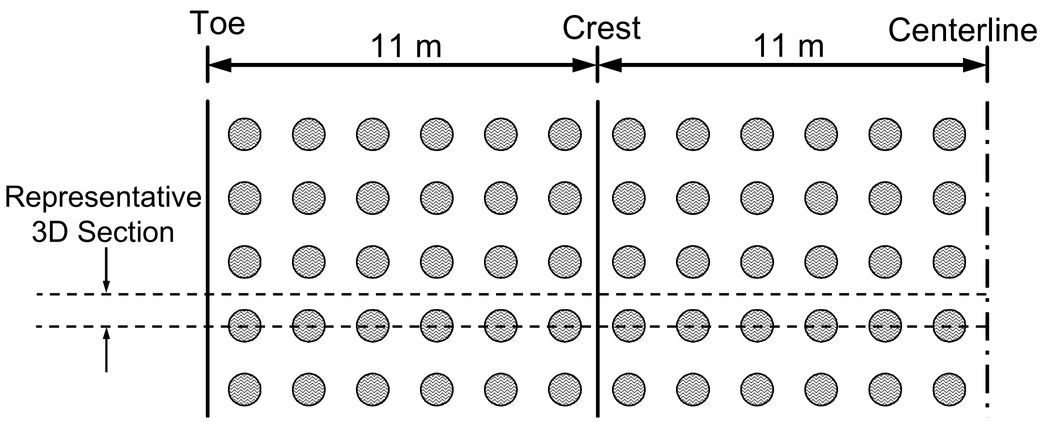
Cross-Section at I-95/Route 1 Test Embankment



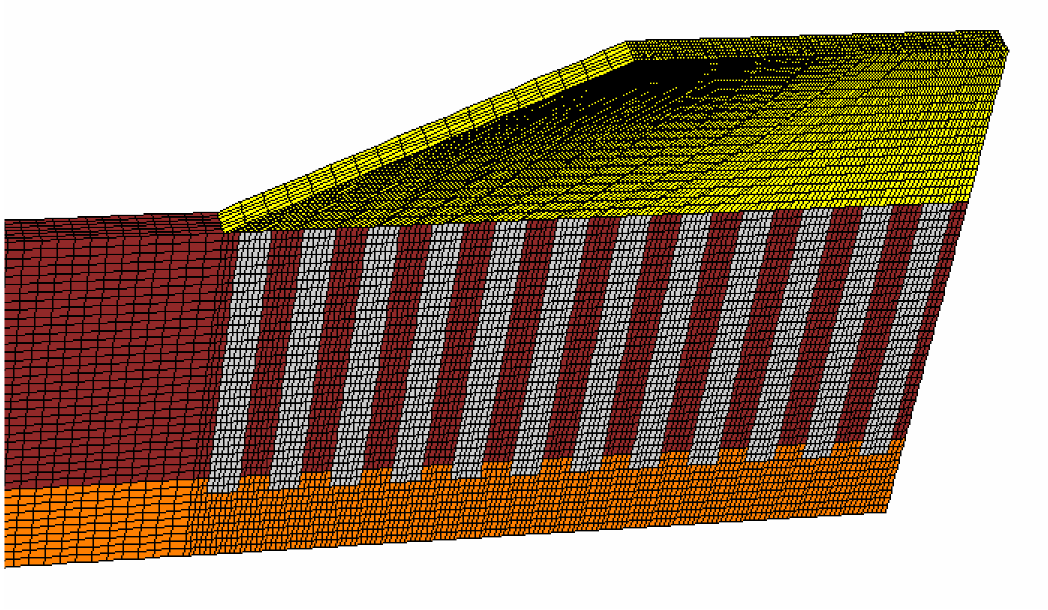
Comparison between Measurements and Calculations for I-95/Rte. 1 Test Embankment



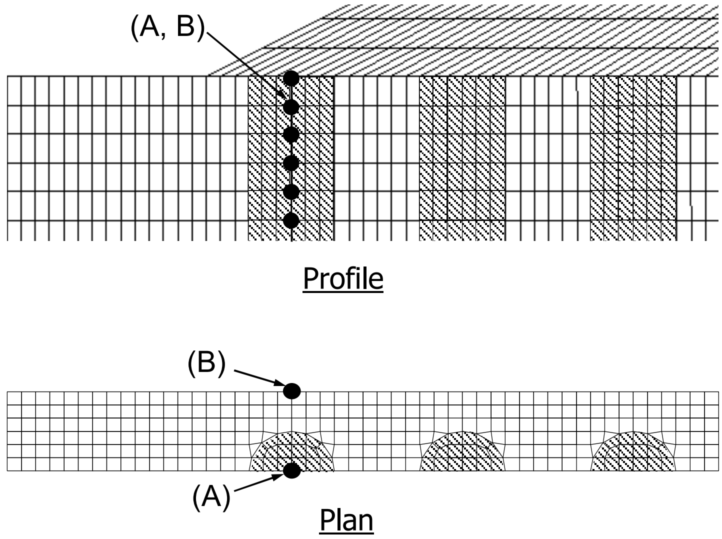
Three-Dimensional Analyses



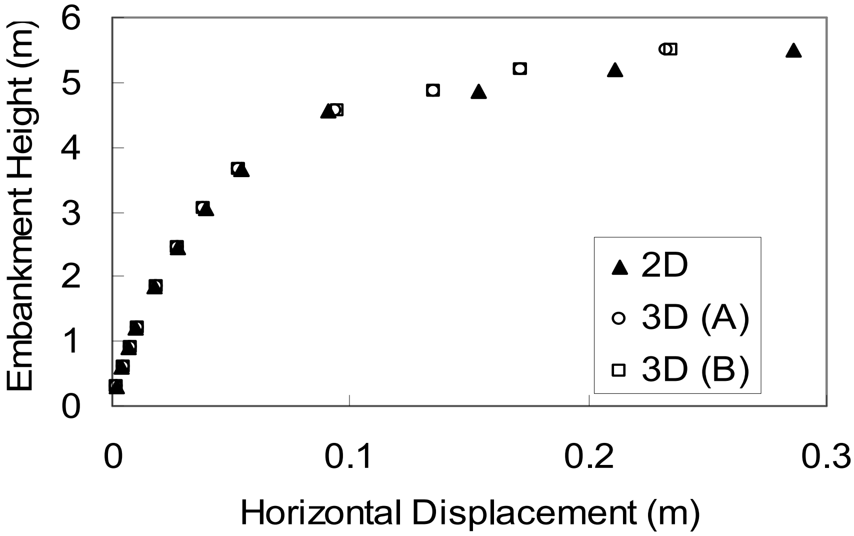
Three-Dimensional Analyses



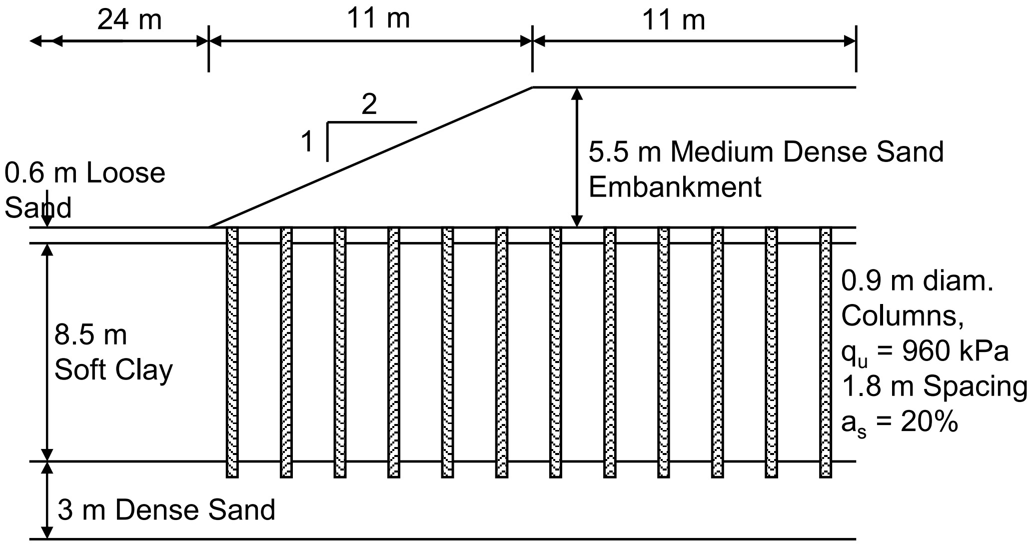
Three-Dimensional Analyses



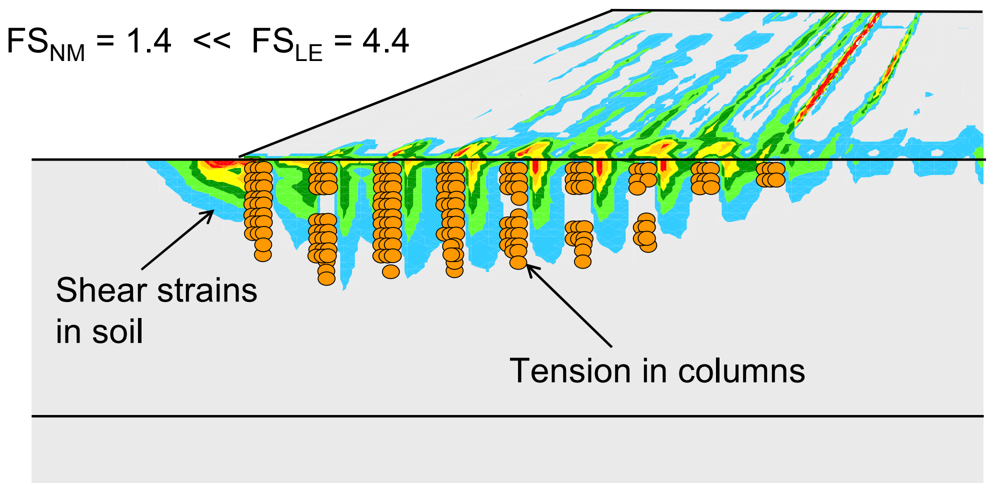
Comparison of 2D and 3D Analyses



Example Embankment



Numerical Slope Stability Analysis



Variability of Deep Mixed Materials

The coefficient of variation of unconfined compressive strength for 13 data sets from 9 deep mixing projects in the U.S. ranges from 0.34 to 0.79 and has an average value of about 0.57

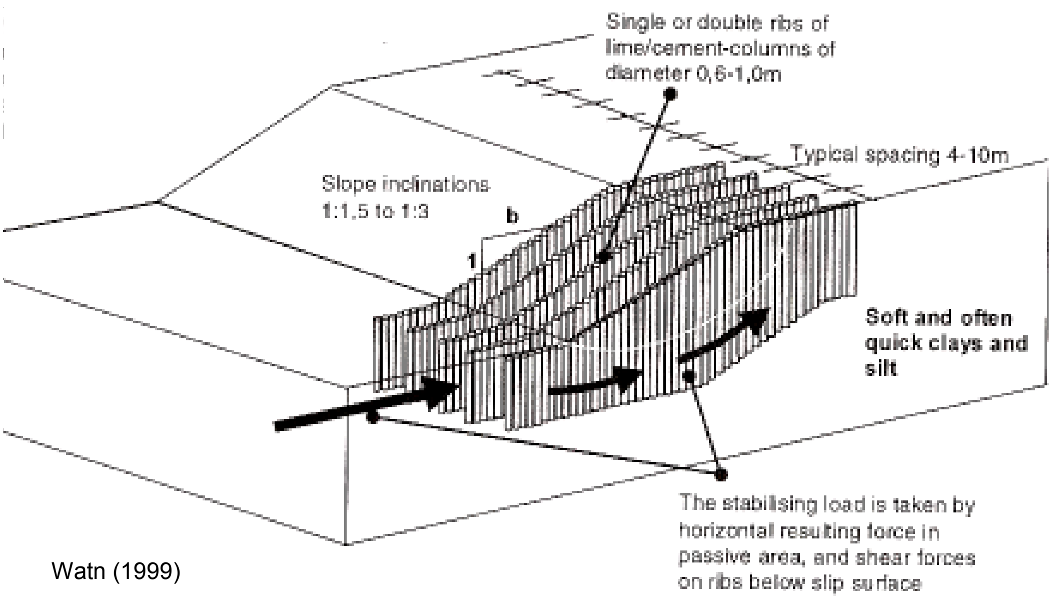
Reliability Analyses of Columns Supported on Deep Mixed Materials

- Because the factor of safety is a highly nonlinear function of the column strength, not all simplified reliability analysis methods work well.
- Of the simplified reliability analysis methods, the Hasofer-Lind method produced the best agreement with more rigorous reliability analysis methods.

Results of Reliability Analyses

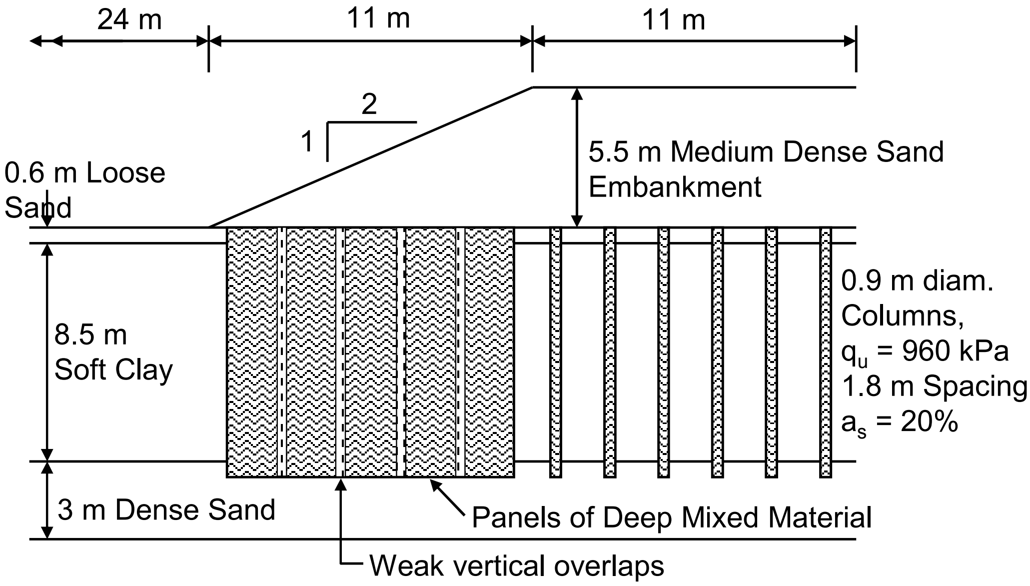
	Limit Equilibrium	Stress-Strain
Factor of Safety	4.4	1.4
Prob. of Failure	0.01%	3.2%

Overlapping columns are often used to stabilize embankment slopes



Watn (1999)

Example Embankment with Panels under Side Slopes



Results of Reliability Analyses

	Isolated Columns Everywhere		Continuous Panels under Slope	
	Limit Equilibrium	Stress-Strain	Limit Equilibrium	Stress-Strain
Factor of Safety	4.4	1.4	4.4	3.1
Prob. of Failure	0.01%	3.2%	0.01%	0.01%

Conclusions: Stability

- Limit equilibrium slope stability calculations can be unconservative by a very large margin
- Numerical analyses of stability are preferred because they allow failure modes like column bending and tilting
- Reliability analyses are needed because of the high variability of deep-mixed material strength
- Panels perform much better than isolated columns under embankment side slopes

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