What You Need to Know to Design or Review a Vendor-Designed Column-Supported Embankment

45th Annual Midwest Geotechnical Conference

James G Collin

jim@thecollingroup.com

the collingroup

Acknowledgments

George Filz

Jie Han

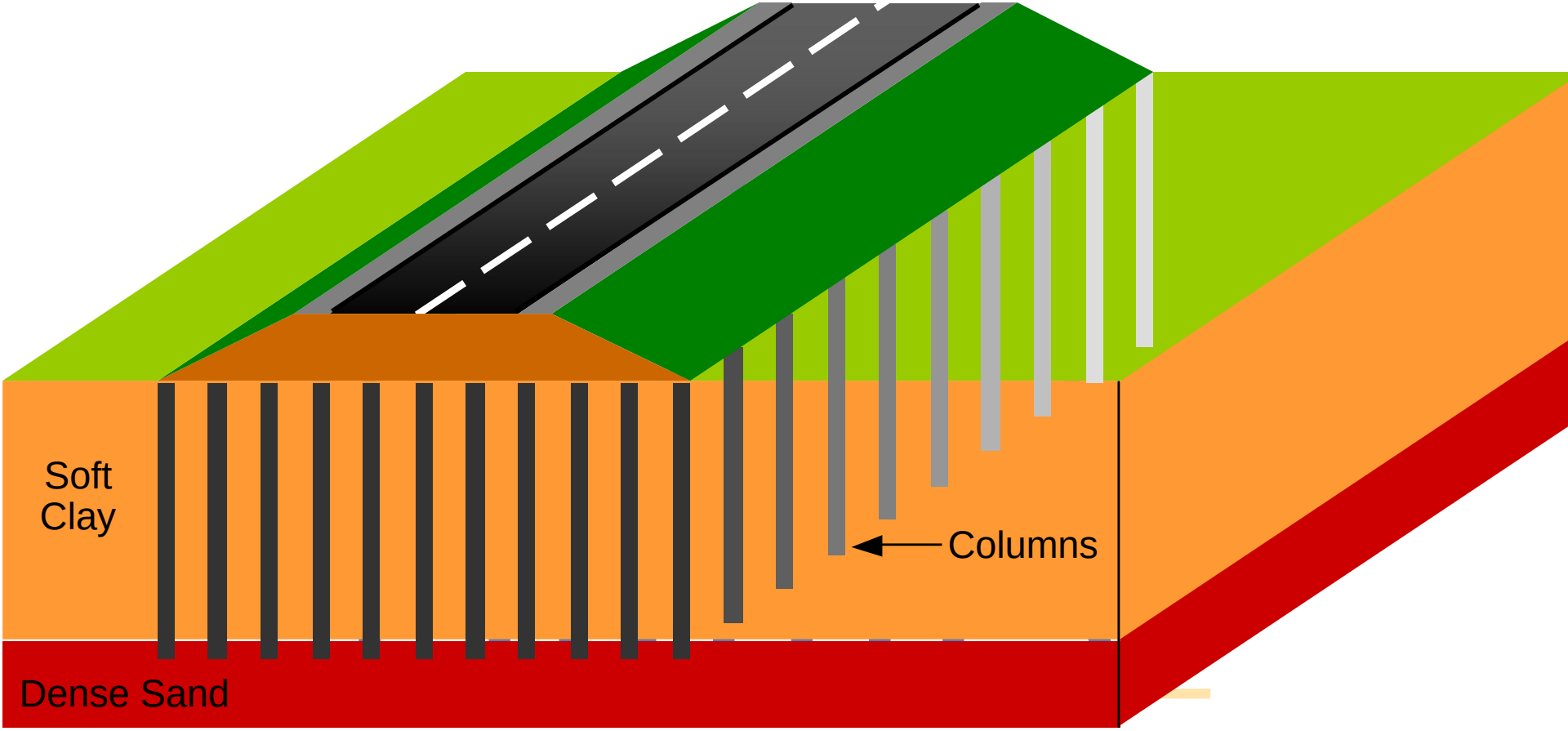
Jie Huang

Mike McGuire

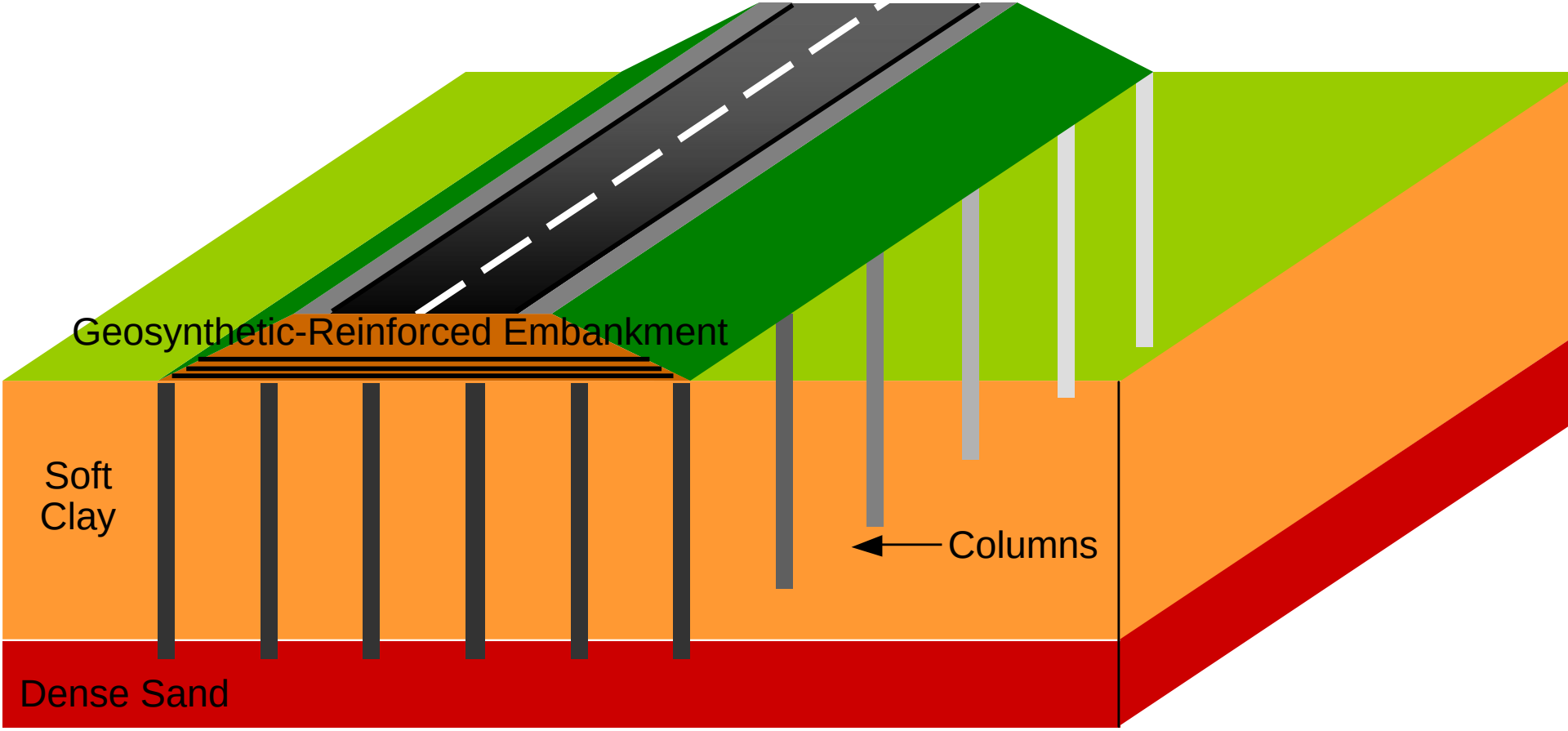
Joel Sloan

Miriam Smith

Conventional CSE



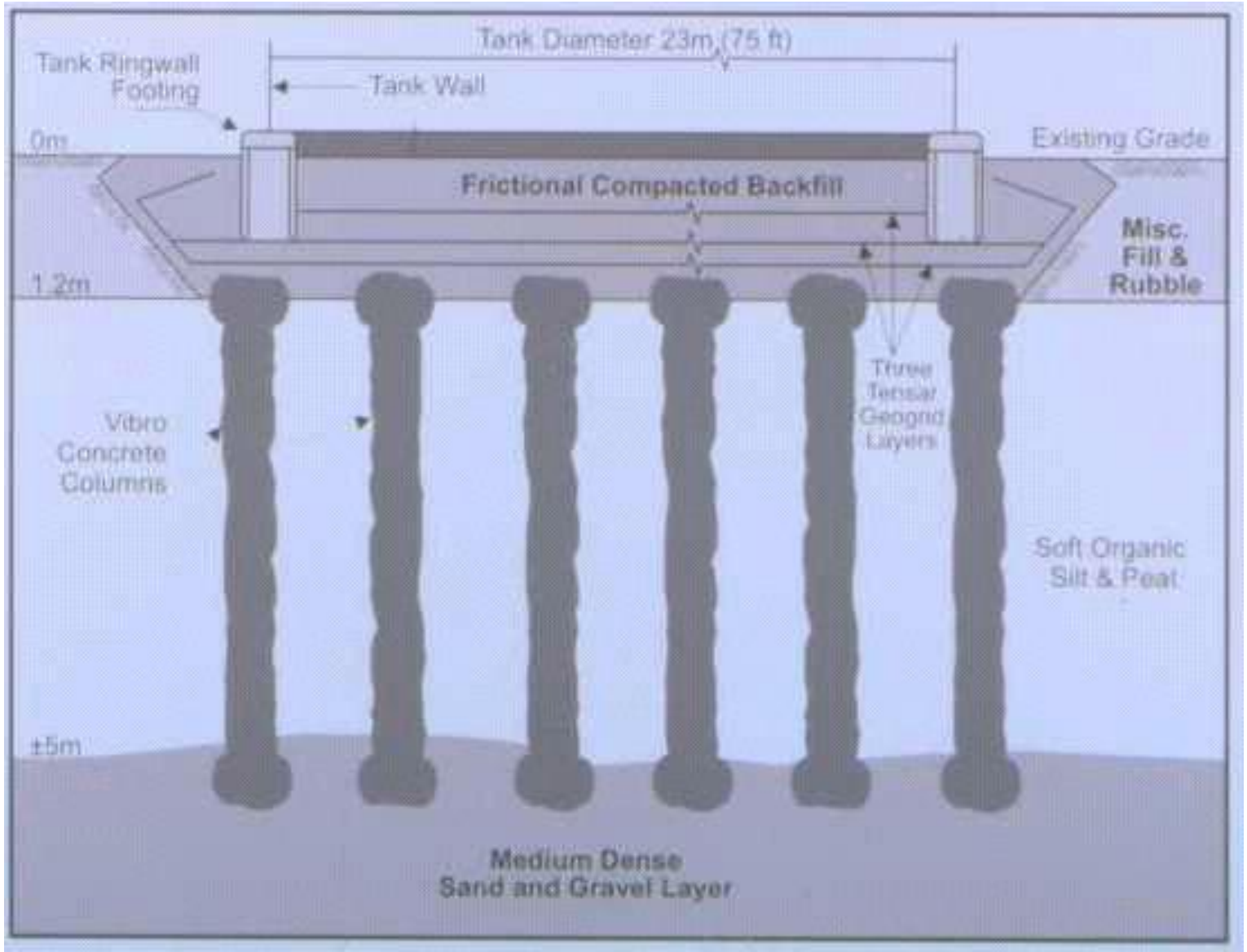
CSE w/ Geosynthetic Load Transfer Platform



Historical Overview

- Developed in Europe in 1980's as rapid construction technique
- First transportation application in 1984 for a bridge approach in Europe using concrete piles and one layer of reinforcement
- First US application was in 1994 for storage tank
- NJ Lightrail supported on CSE with VCC in 2001
- 2016 Projects have been completed in Al, DC, FL, IA, GA, LA, MD, MN, NC, ND, NJ, NY, SC, TX, VA, and WA.

Westway Terminal - 1996

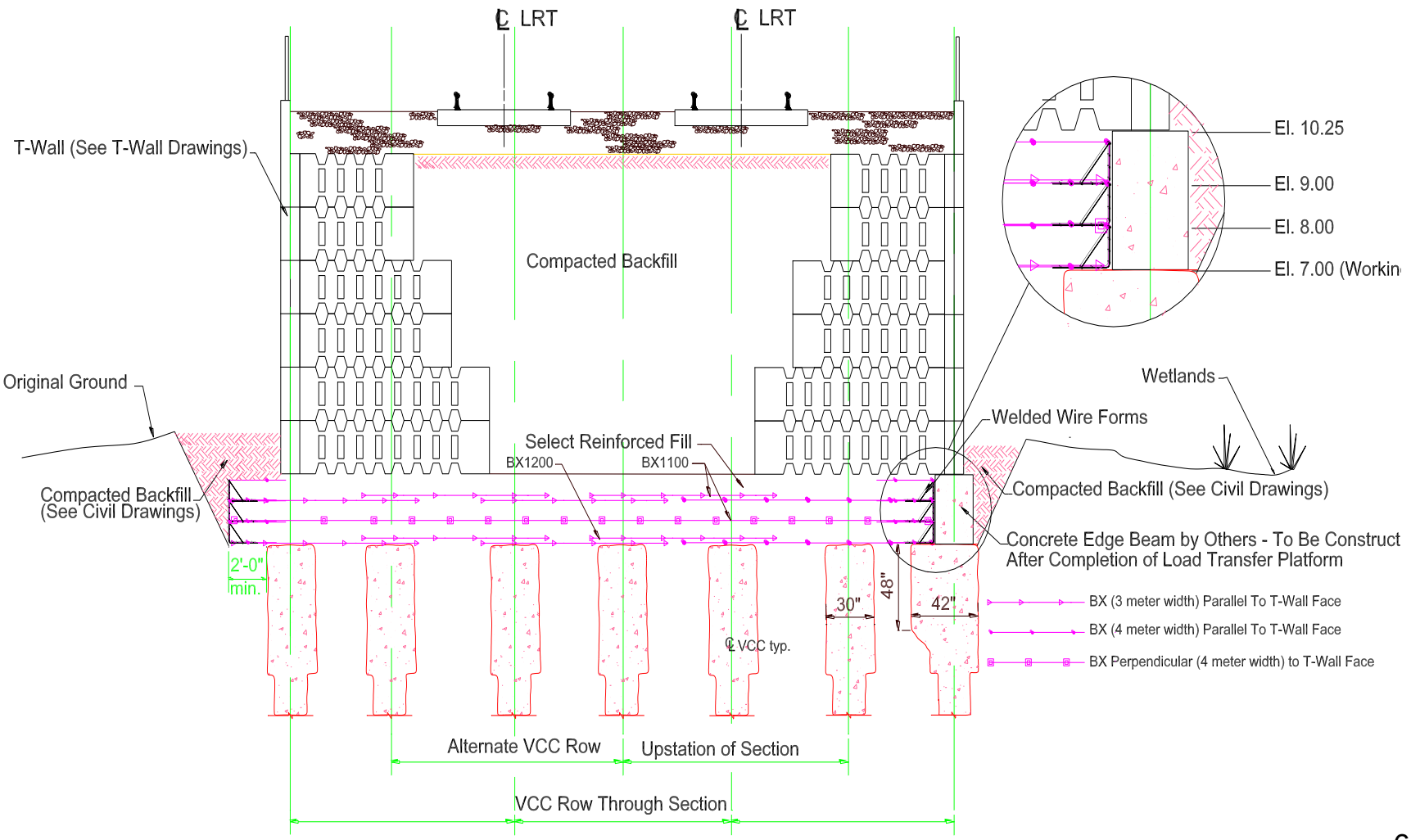


Westway Terminal

Westway Terminal

Westway Terminal

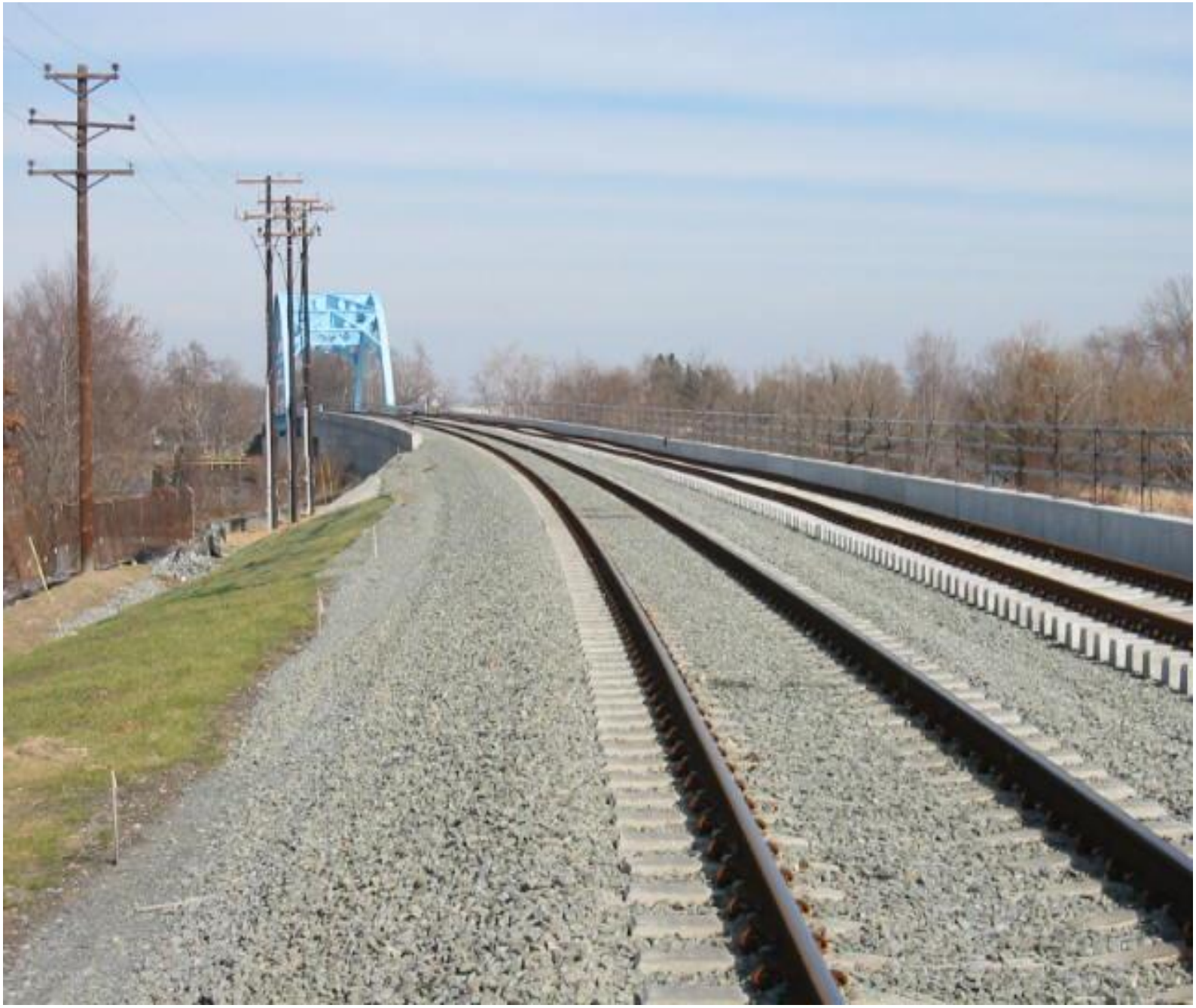
1st US Transportation Related Project - Rancocas Creek, NJ



Column Installation

LTP Construction

KOMATSU
CATERPILLAR
CAT
HOLT
11-0798
BECHTEL
03 09 2001 15:52



Applications

- Embankment stabilization
- Roadway widening
- Bridge approach fill stabilization
- Bridge abutment and other foundation support

What are the advantages of CSE?

- Rapid construction relative to follow on work
- Eliminate staged construction
- Not limited to a specific columns type
- Reduce/eliminate settlement problems
- Reduce/eliminate stability problems

Feasibility Evaluation – Criteria for Successful Application

- Column spacing based on area replacement ratio 3-10%
- Embankment height > Critical Height
- Clear span between columns < 10 feet
- Embankment height greater than clear span between columns
- LTP backfill friction angle > 35°
- Columns designed to carry full embankment load

Column Characteristics

Column Type	Range of Allowable Capacity (kips)	Typical Lengths (feet)	Typical Column Diameters (inches)
Timber pile	25-100	20-60	12-18
Steel H pile	100-450	30-100	10-14
Steel pipe pile	175-550	30-120	10-48
Pre-cast concrete piles	100-450	30-50	10-24
Cast-in-place concrete shell (mandrel driven)	100-300	20-120	10-18
Shells driven without mandrel	110-300	20-75	12-36
Continuous Flight Auger piles	75-150	20-75	12-24
Deep mix method (DMM)	90-275	20-90	24-78
Aggregate Columns	25-150	10-30	24-48
VCC	50-300	20-90	18-24
CSV (combined soil stabilization)	5-10	10-30	5-7
CMC	50-150	20-90	12-24

Benefits of Pile Caps

- Reduce clear span between columns
- Reduce potential for punching failure through embankment

Load Transfer Platforms (LTP)

Geosynthetic reinforced soil mass designed to transfer load from above the platform to columns below the platform

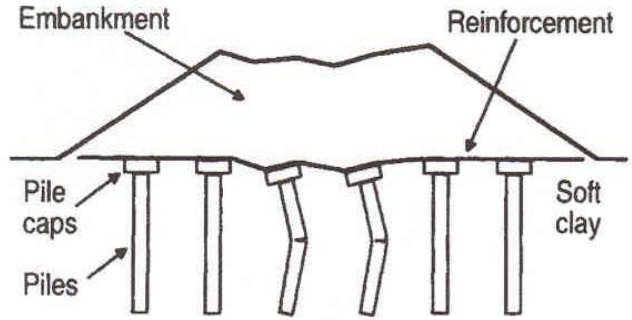
What type of geosynthetic reinforcement would you use for this application?

- High Strength Woven Geotextile
- Uniaxial Geogrid
- Biaxial Geogrid

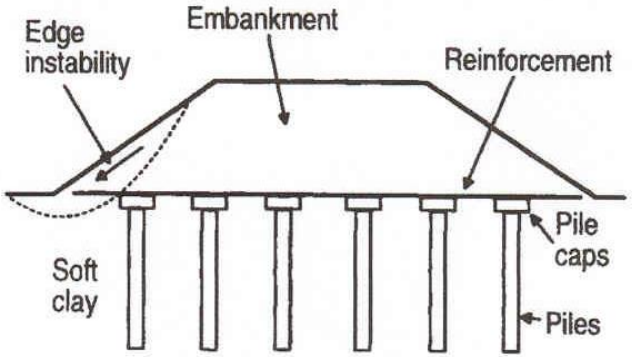
LTP Select Fill

- Arching in the LTP is considered an integral component in stress transfer from embankment to columns
- Well graded granular soil is preferred
- Material with an effective friction angle > 35 degrees

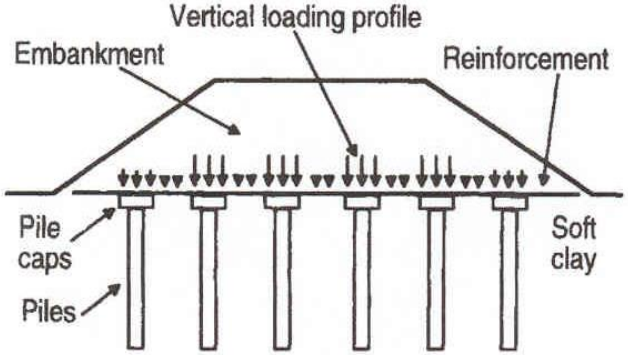
Design Concepts – Failure Modes



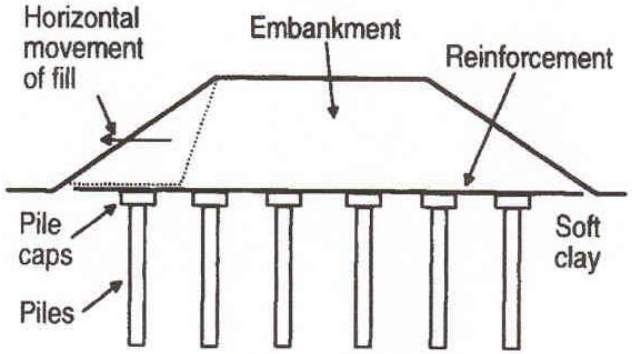
a) Pile group capacity



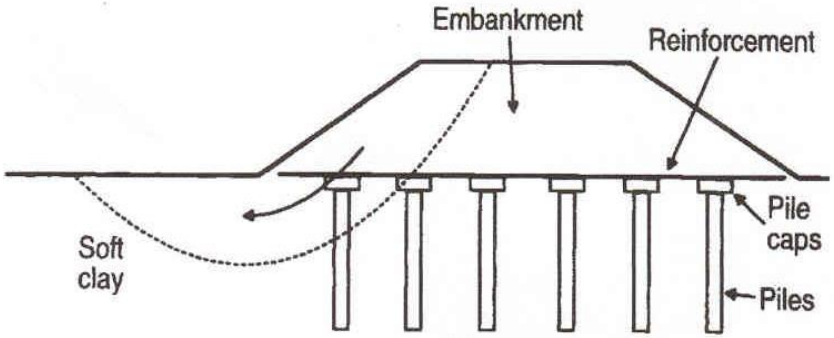
b) Pile group extent



c) Vertical load shedding

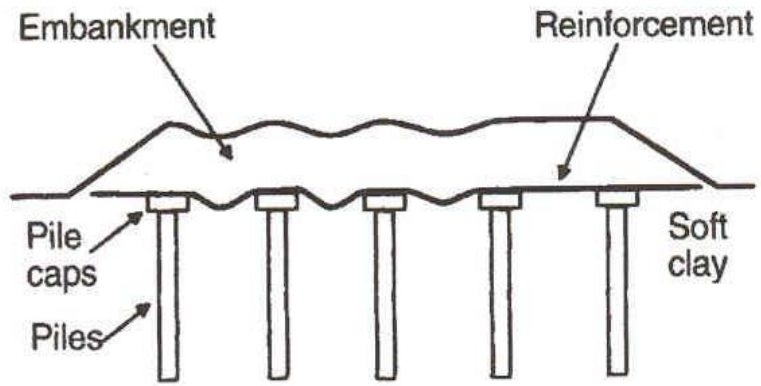


d) Lateral sliding

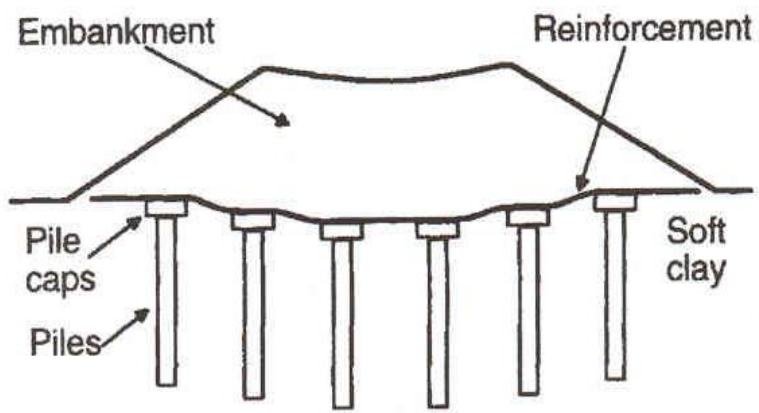


e) Overall stability

Design Concepts – Serviceability State



a) Reinforcement strain



b) Foundation settlement

Design Steps

1. Estimate preliminary column spacing.
2. Determine required column load.
3. Select preliminary column type based on column load and site geotechnical requirements.
4. Determine capacity of column to satisfy limit and serviceability state design requirements.

Design Steps cont.

5. Determine extent of columns required across the embankment width.
6. Check critical embankment height criteria and adjust column spacing if required.
7. Determine if LTP is required.
8. If LTP is reinforced, determine reinforcement requirements based on estimated column spacing (steps 1 & 6). Revise column spacing as required.

Design Steps cont.

9. Determine reinforcement requirements for lateral spreading.
10. Determine overall reinforcement requirements based on LTP and lateral spreading.
11. Check global stability.
12. Prepare construction drawings and specifications.
13. Observe construction.

Column Design Steps

- Determine geotechnical characteristics of foundation soil
- Determine load in columns
- Select preliminary column type/types
- Calculate column capacity and length
- Consider deformation characteristics of column types (i.e., stone columns 30 –50% settlement)

Column Required Load

$$Q_r = A_{unitcell} (\gamma H + q)$$

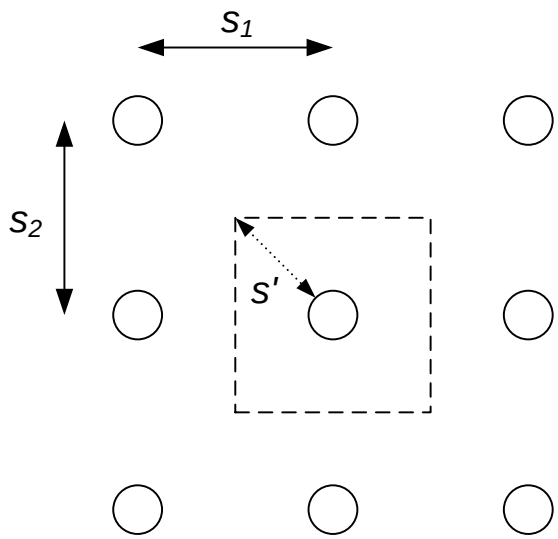
$A_{unitcell}$ = from figure 6-10

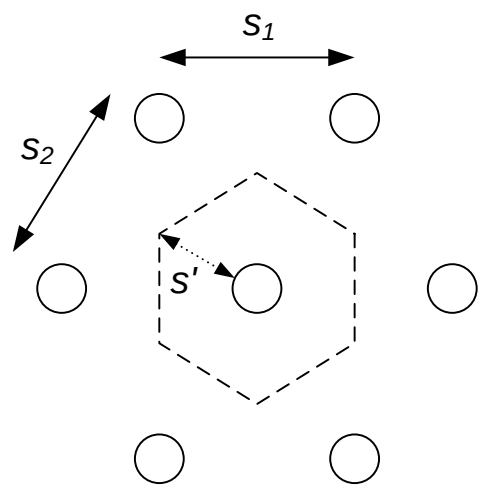
H = height of embankment

q = live and dead load surcharge (typically 250 psf)

γ = unit weight of the embankment soil

Column Required Load



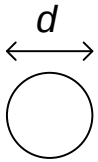


$A_{unitcell} = s_1 * s_2$

$s' = (s_1^2 + s_2^2)^{1/2}/2 - d/2$

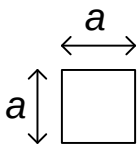
$A_{unitcell} = s_1(s_2^2 - s_1^2/4)^{1/2}$

$s' = (s_2^2 + 2s_1^2)^{1/2}/3 - d/2$



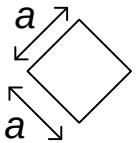
$A_c = \pi d^2/4$

$p = \pi d$



$A_c = a^2$

$p = 4a$



$A_c = a^2$

$p = 4a$

To convert between square and round columns, an equal area conversion is recommended where $a = 0.886 * d_{col}$

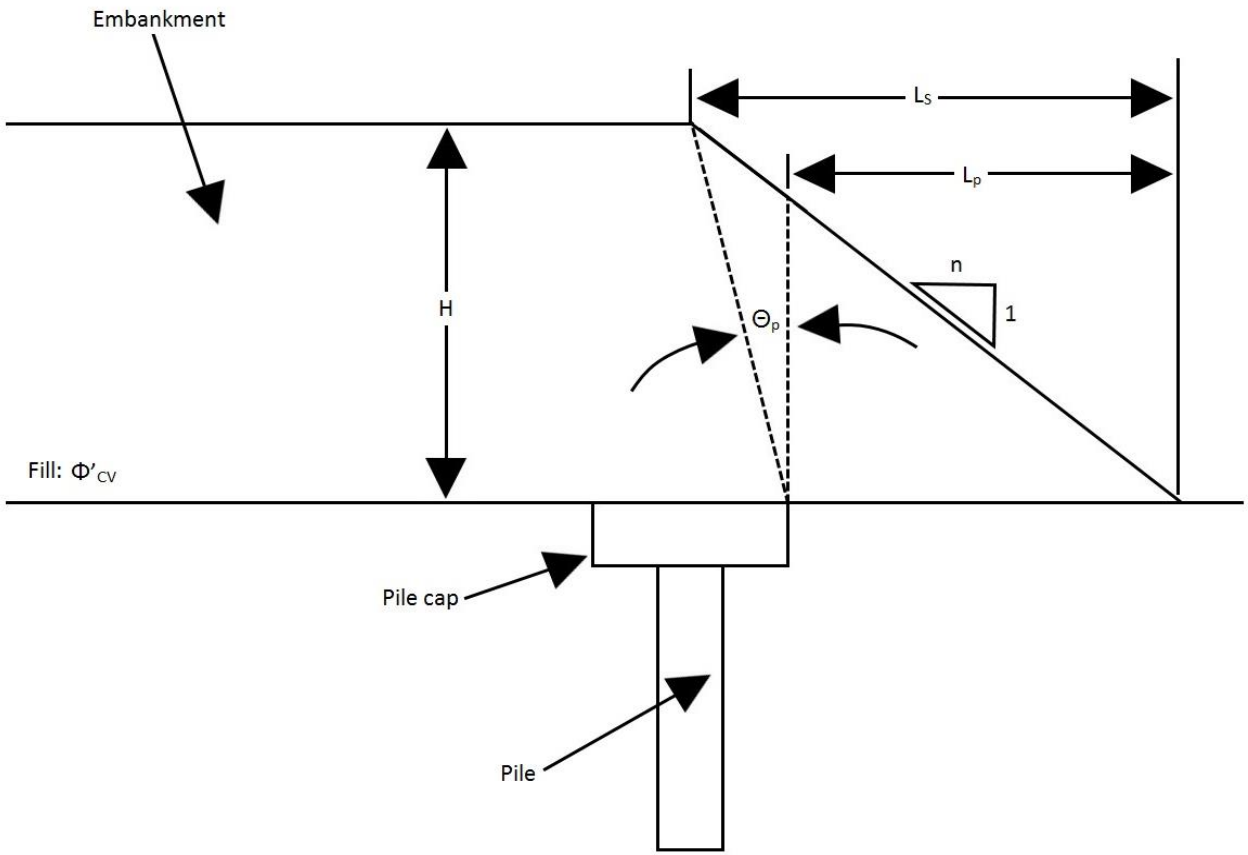
Preliminary Column Layout

- Column spacing 5 ft – Column loads 25-50 kips for 10-30 ft high embankment
- Column spacing 10 ft – Column loads 90-250 for 10-30 ft high embankment
- Column costs typically represent 85-95% of construction cost

Geotechnical Column Capacity

- Driven Piles – GEC 12
- Timber Piles – Timber Pile Design and Construction Manual
- Continuous flight auger piles – GEC 8
- VCCs, aggregate columns, and soil mixing – see pertinent Technical Summary

Lateral Extent of Columns



Lateral Extent of Columns

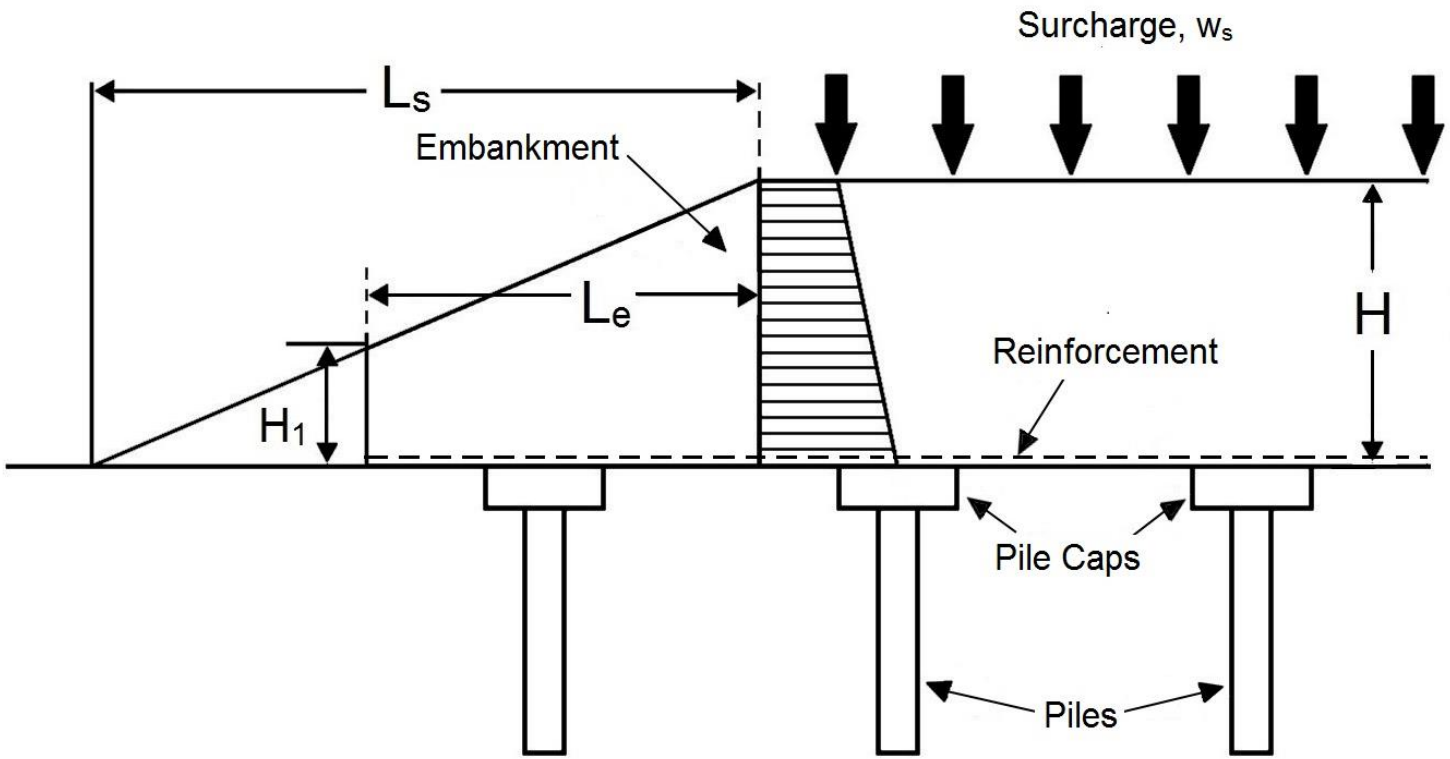
$$L_p = H\,(n - \tan\theta_p)$$

n = side slope of the embankment

$\theta_p = (45 - \varphi_{emb}/2)]$

φ_{emb} = effective friction angle of embankment fill

Lateral Spreading



Lateral Spreading cont.

Determine the driving force P_{lat}

$$P_{Lat} = K_a (\gamma H^2/2 + qH)$$

where:

K_a = coefficient of active earth pressure

$= \tan^2 (45^o - \varphi_{emb}/2)$

Lateral Spreading cont.

Determine the resisting force w/o a geosynthetic R_{ls}

$$R_{ls} = (L_s)\, S_u$$

where:

S_u = undrained shear strength of the foundation soil

L_s = length of the side slope of the embankment

Lateral Spreading cont.

$$FS = R_{ls}/P_{Lat} \geq 1.5$$

If FS< 1.5 add a geosynthetic reinforcement layer

$$T_{ls} \geq P_{Lat}$$

Lateral Spreading cont.

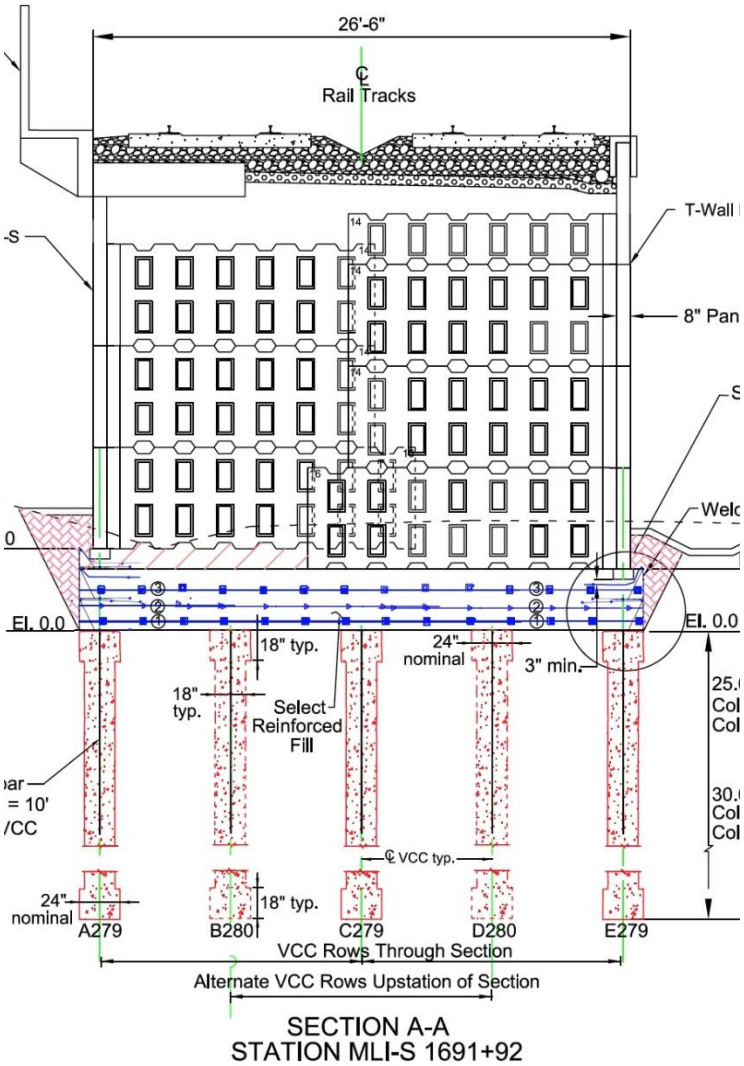
Determine the anchorage length of reinforcement from the following equation:

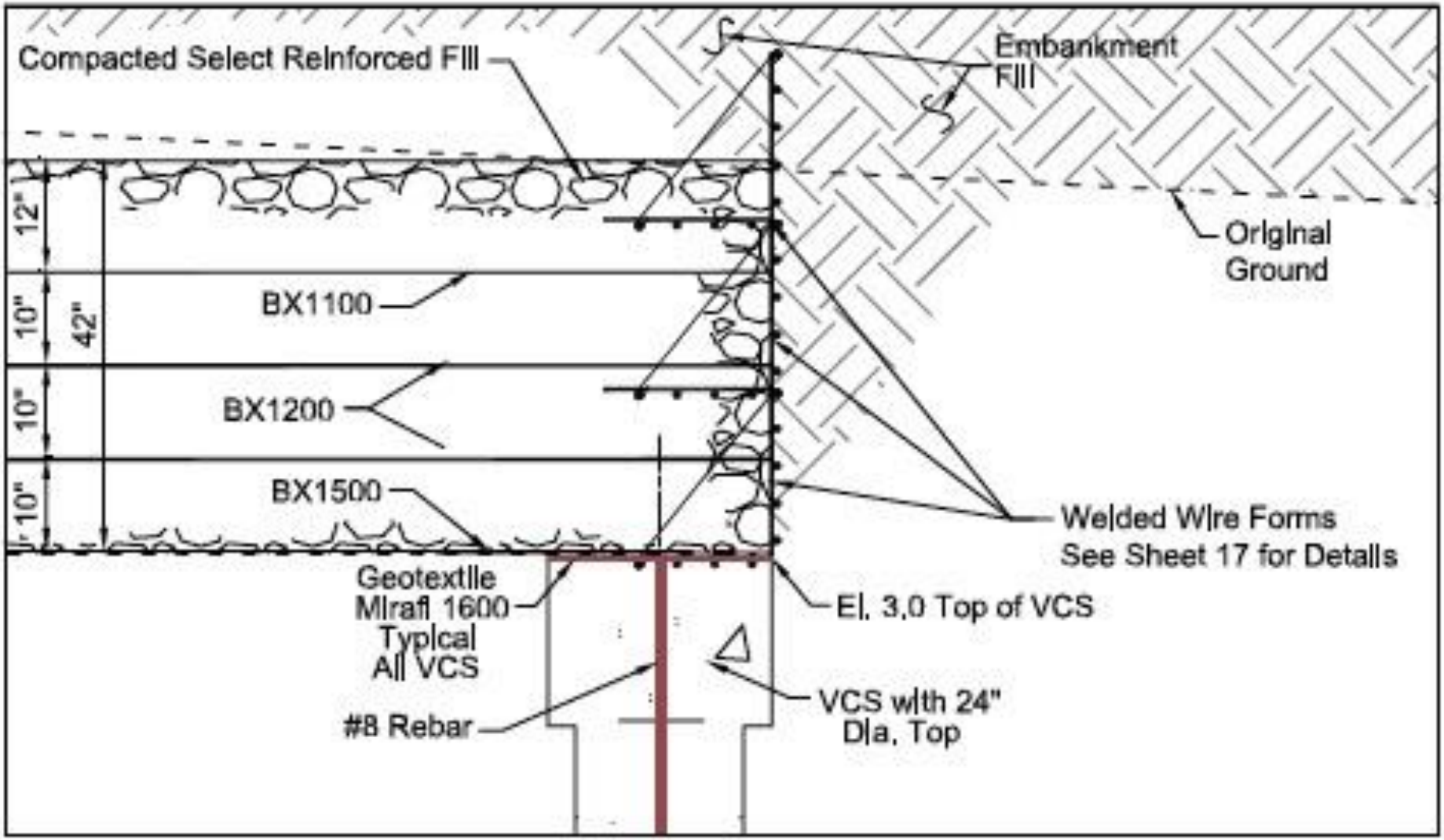
$$L_e = P_{Lat} /[(0.5 (\gamma (H)(c_{iemb} \tan \varphi_{emb})]$$

where:

c_{iemb} = coefficient of interaction for sliding between the geosynthetic reinforcement and embankment fill

If the sides of the embankment consist of MSE Retaining Walls in lieu of slopes how do you ensure adequate anchorage?

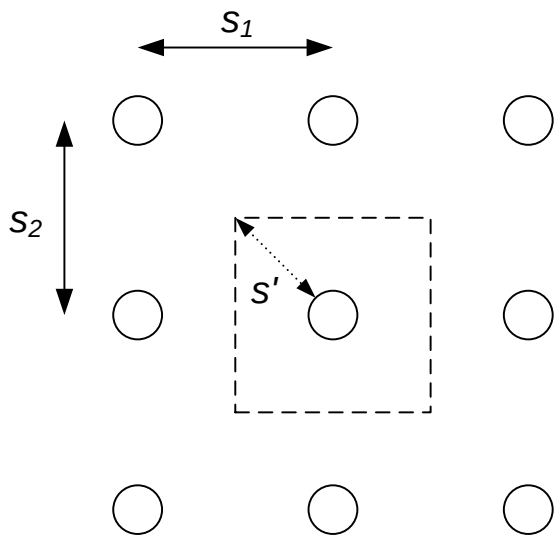


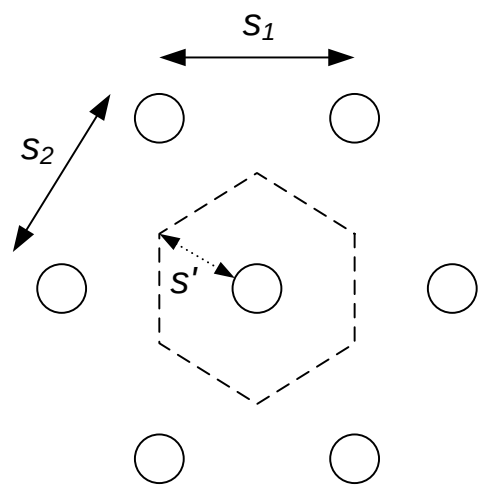

Compacted Select Reinforced Fill
Embankment Fill
Original Ground
12"
10"
10"
10"
42"
BX1100
BX1200
BX1500
Welded Wire Forms
See Sheet 17 for Details
Geotextile
Mirafi 1600
Typical
All VCS
El. 3.0 Top of VCS
#8 Rebar
VCS with 24"
Dia. Top

Critical Height

$$H > H_{crit} = \max\left\{ \begin{array}{c} 1.5 \cdot (S - a) \\ 1.15 \cdot S' + 1.44 \cdot d \end{array} \right\}$$

Critical Height Terms



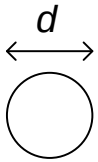


$A_{unitcell} = s_1 * s_2$

$s' = (s_1^2 + s_2^2)^{1/2}/2 - d/2$

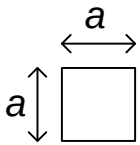
$A_{unitcell} = s_1(s_2^2 - s_1^2/4)^{1/2}$

$s' = (s_2^2 + 2s_1^2)^{1/2}/3 - d/2$



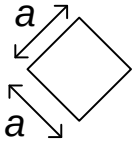
$A_c = \pi d^2/4$

$p = \pi d$



$A_c = a^2$

$p = 4a$



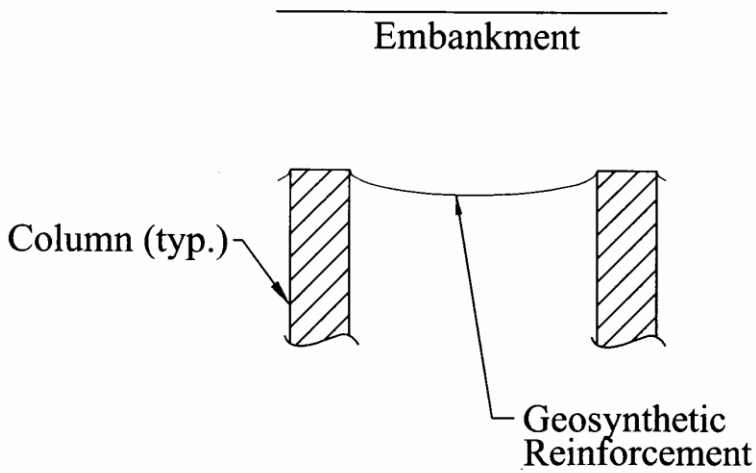
$A_c = a^2$

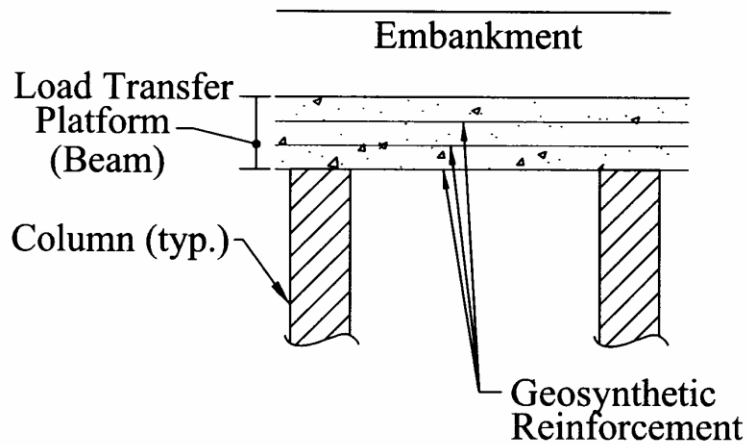
$p = 4a$

To convert between square and round columns, an equal area conversion is recommended where $a = 0.886 * d_{col}$

LTP Design

Design Concepts – Geosynthetic Design





Catenary Theory

Beam Theory – Load Transfer Platform

Catenary or Beam Design

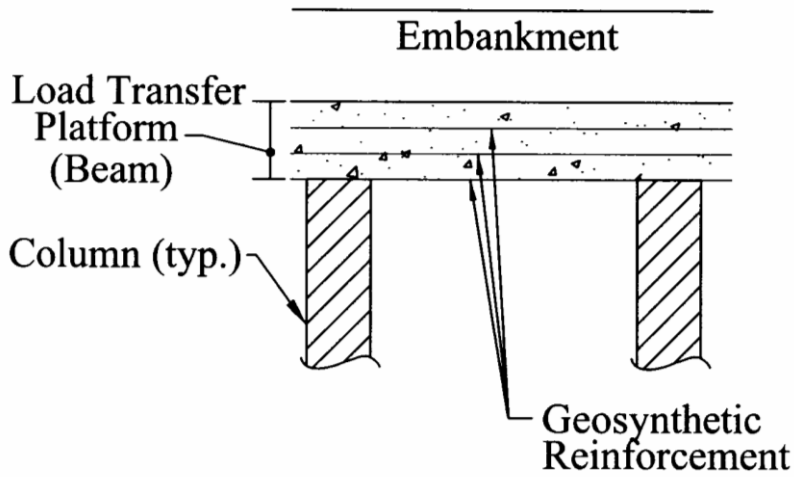
- Empirical
- Theoretical
- Numerical Modeling

Beam Method - Empirical Approach Criteria for Successful Application

- Clear span between columns < 10 feet
- Embankment height greater than 1.6 times the clear span between columns
- Thickness of LTP > 0.5 clear span
- LTP backfill friction angle > 35°
- Columns designed to carry full embankment load

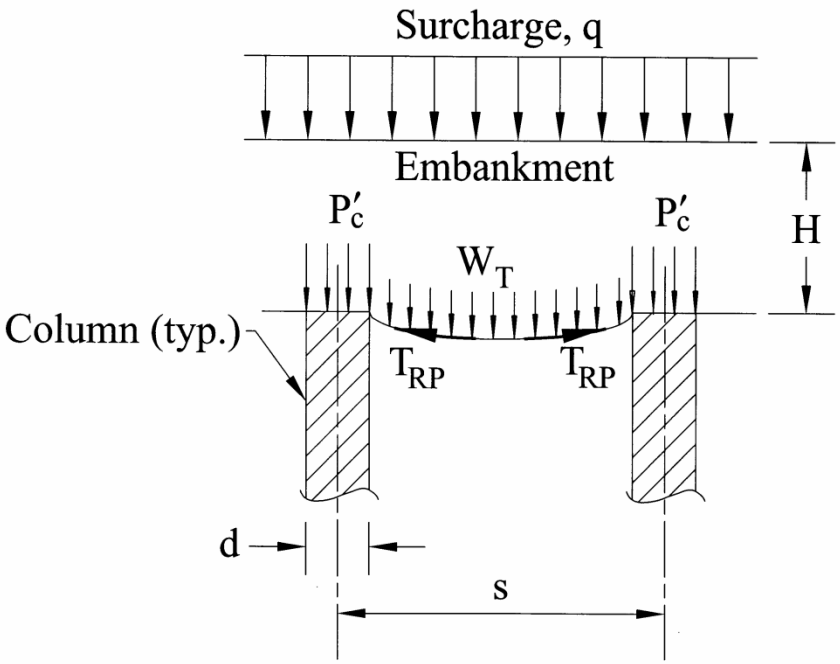
Empirical LTP Design – Beam Theory Assumptions

- Minimum three layers of reinforcement
- Spacing between layers 20-45 cm
- Platform thickness ≥ ½ clear span between columns
- Soil arch is fully developed within the depth of the platform



Empirical Design Steps - Geosynthetic

- Determine vertical load (W_T) from the embankment to be carried by the geosynthetic
- Determine the tensile force in the geosynthetic T_{RP}
- Select reinforcement based on design requirements



Empirical Beam Design

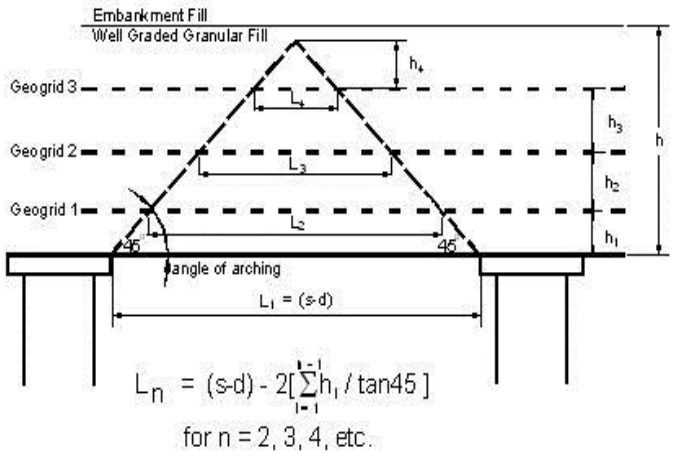
$$W_{Tn} = [A_n + A_{n+1}]\, h_n\, \gamma / 2\, A_n$$

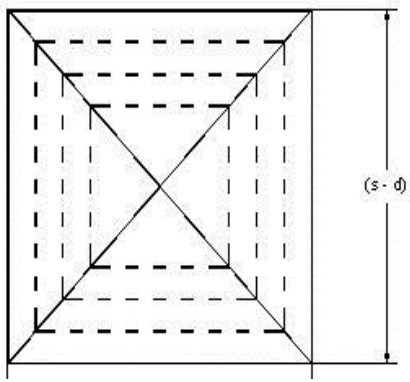
$$T_{rpn} = W_{Tn}\, \Omega\, D/2$$

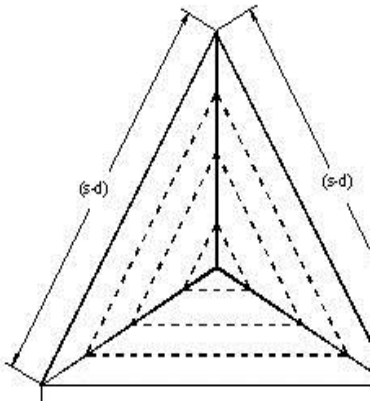
where:

A_n = plan area of the reinforcement at layer n

Ω = dimensionless factor for tension membrane theory (varies between 1-2 for strain of 5% -1%)



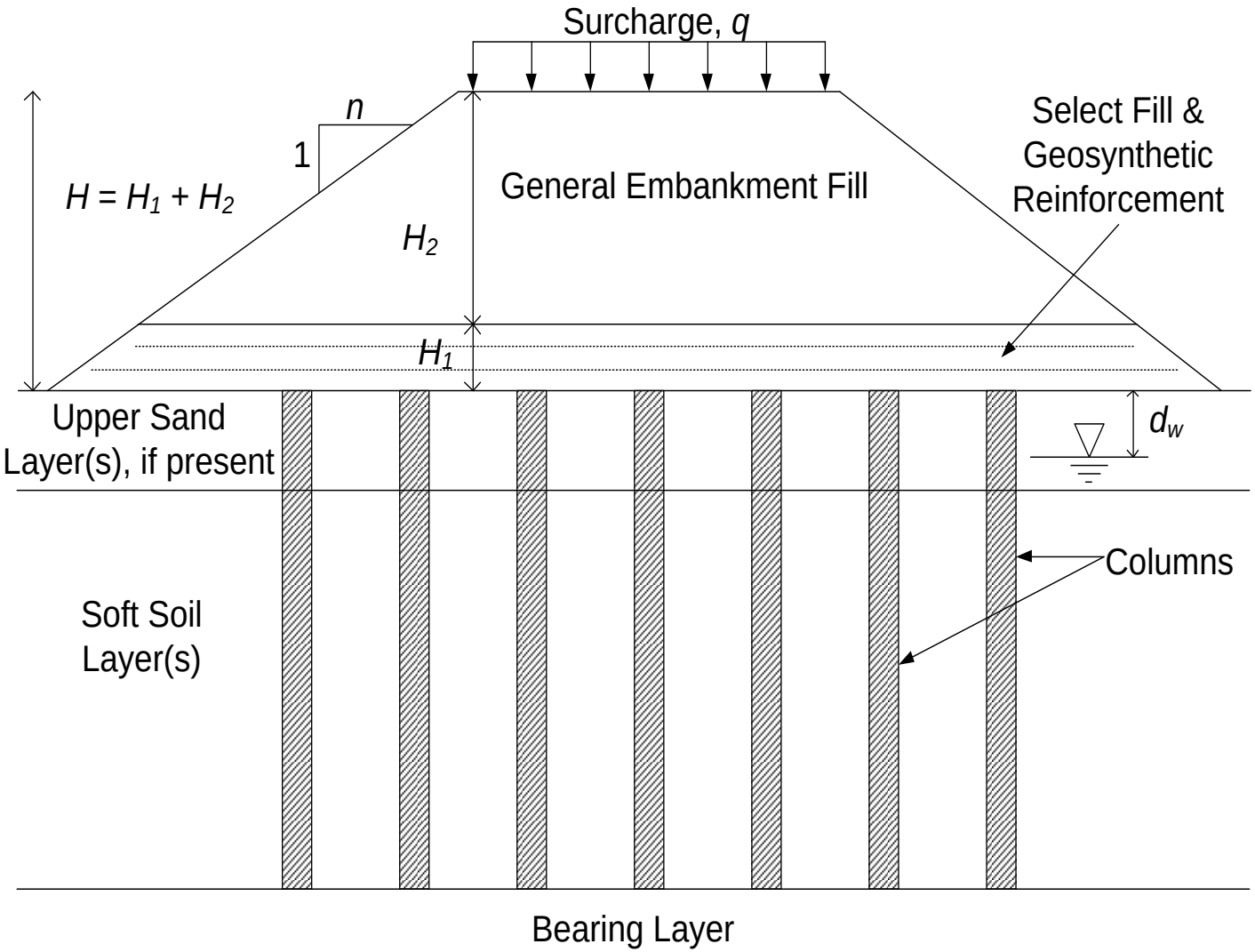




What are the Limitations of the Empirical Beam Method ?

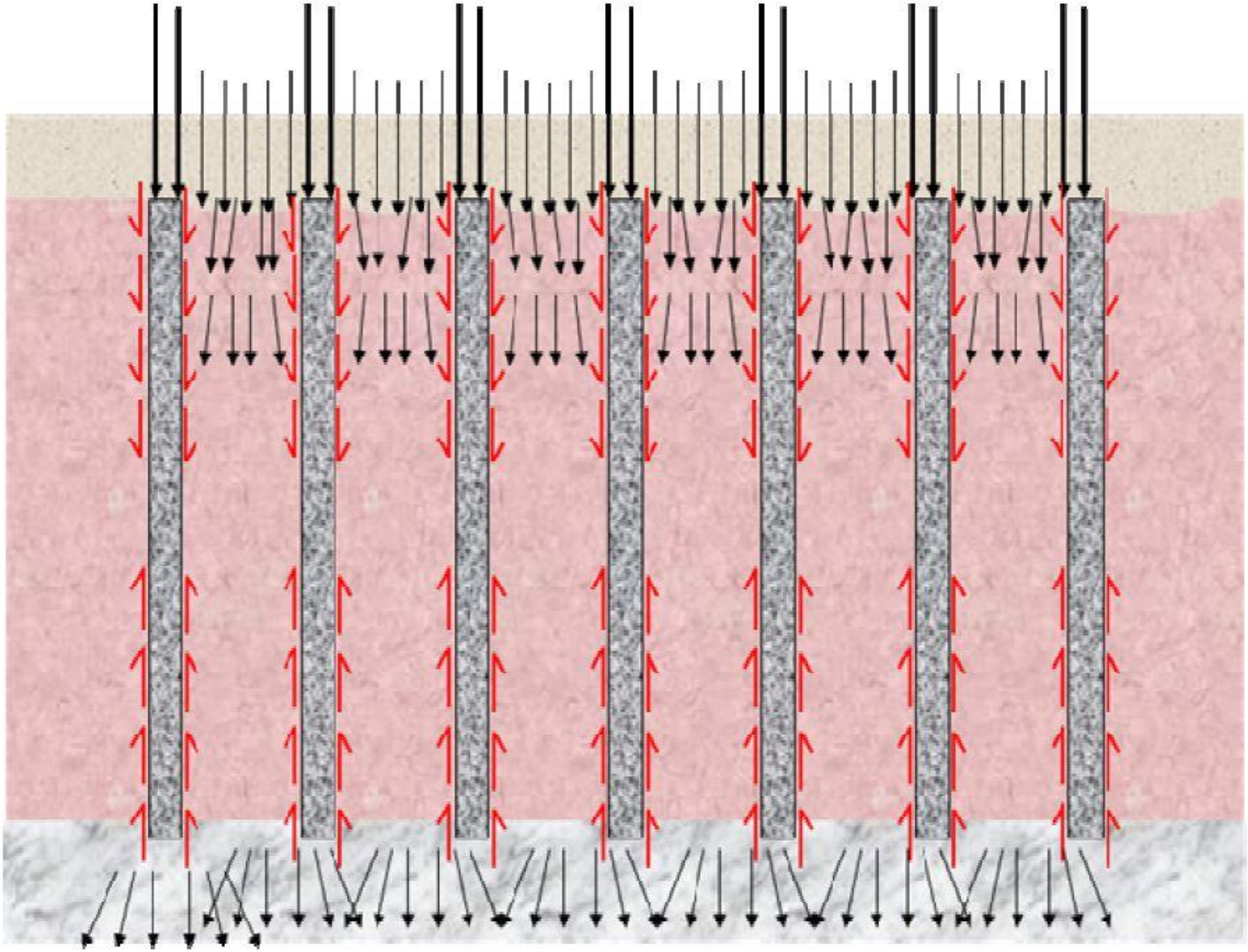
- Does not consider subgrade strength in evaluating geogrid requirements
- No capability to calculate deformations
- Simplistic model considers only one soil type
- Based on experience of one practitioner
- Cannot determine what is the actual FS

LTP Design cont.

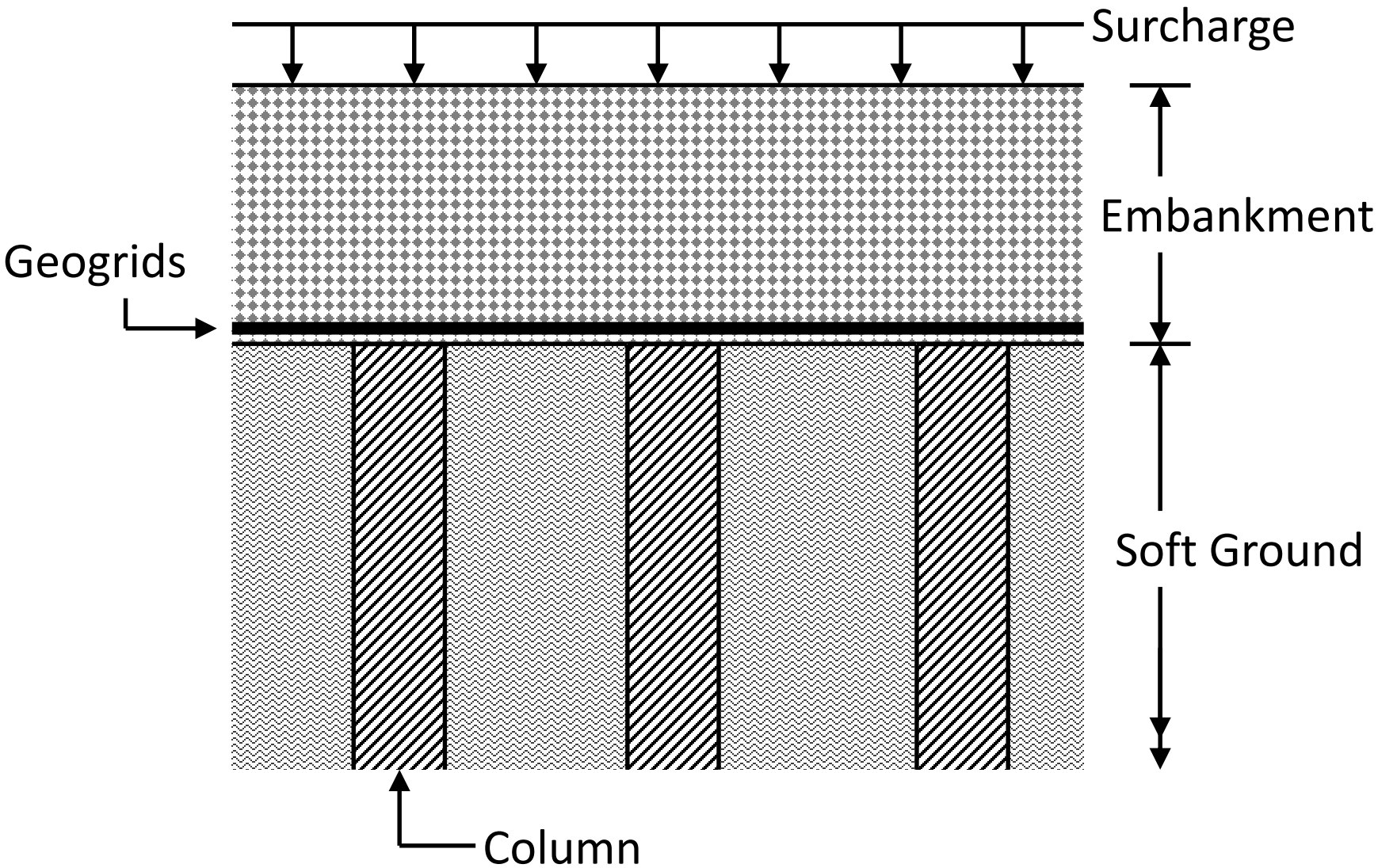


Theoretical Approach Based on Load and Displacement Compatibility - 2005

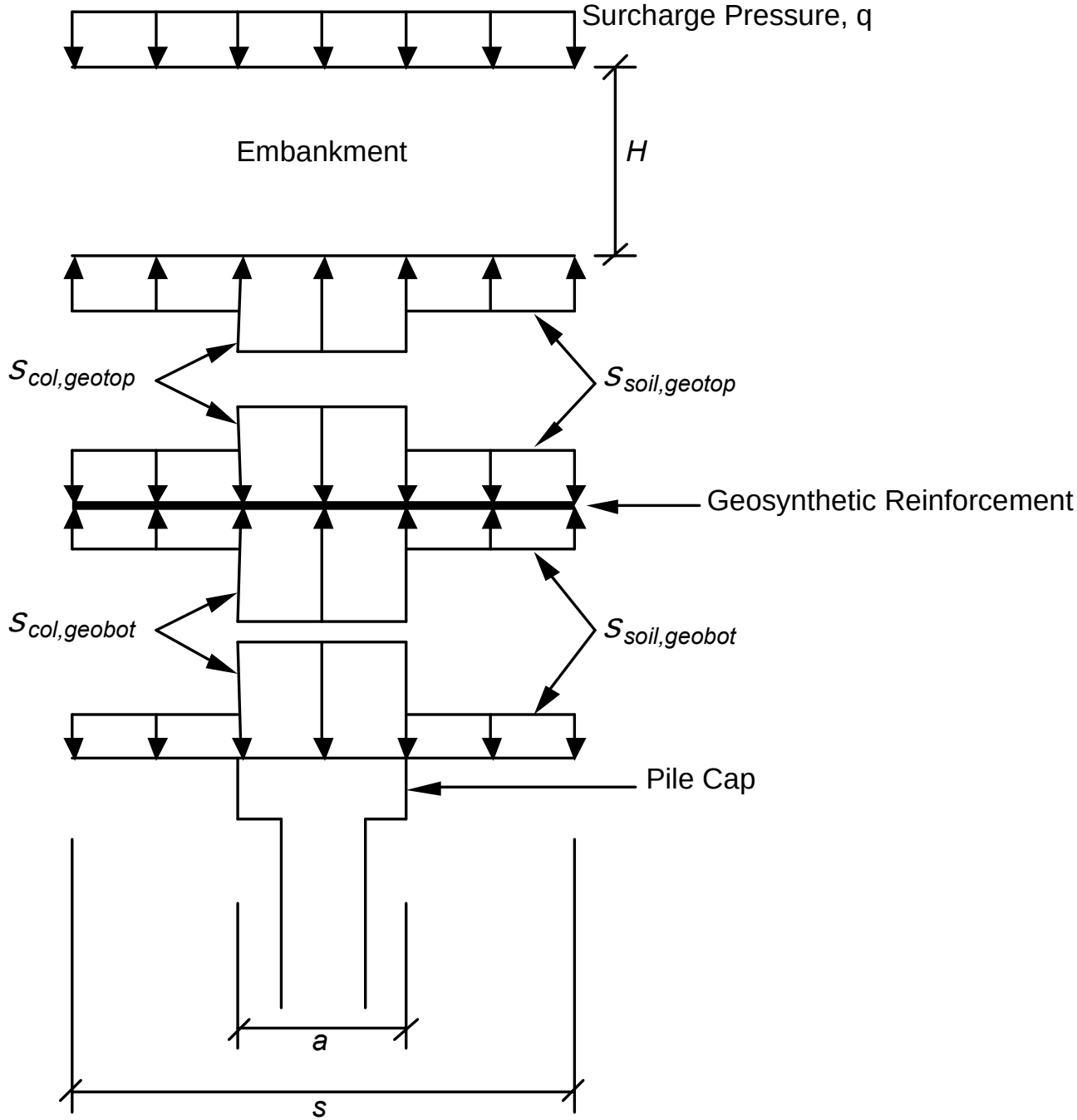
- Load from embankment
  - Linear elastic solution prior to full strength mobilization, based on differential settlement between column and soil
- Geogrid support included
- Support from soil between columns
  - Upper layers of existing sand allowed
  - Underlying clay layers have nonlinear compressibility (i.e., characterized by C_c, C_r, p_p)
  - Load transfer from soil to columns through skin friction
- Column and soil compression calculated over depth to equal settlement



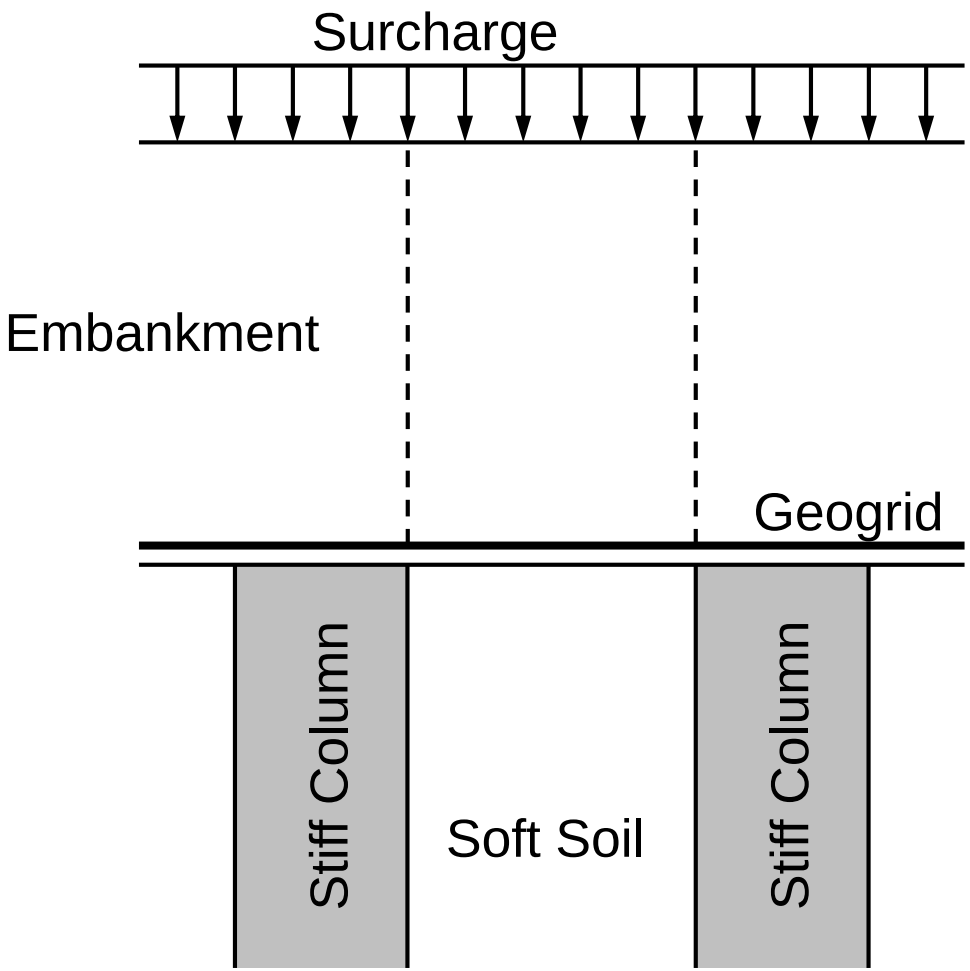
Schematic Diagram of Column-Supported Embankment

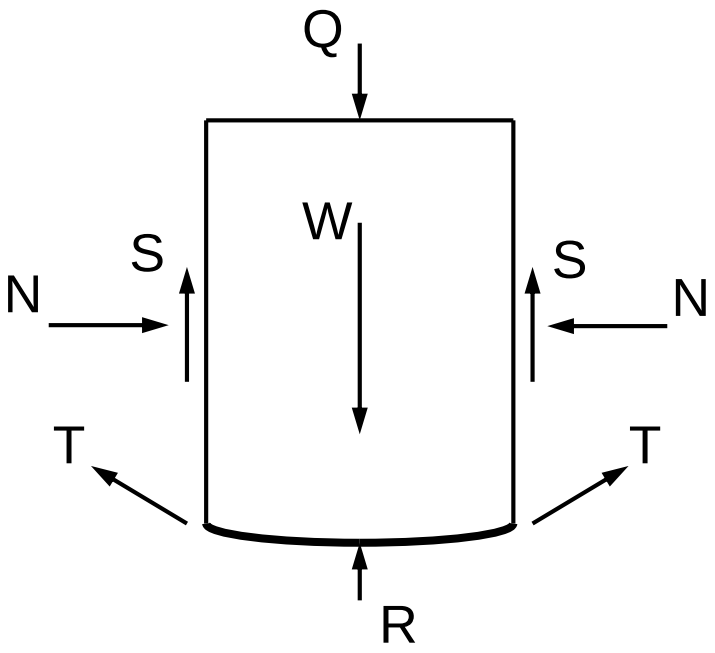


Unit Cell

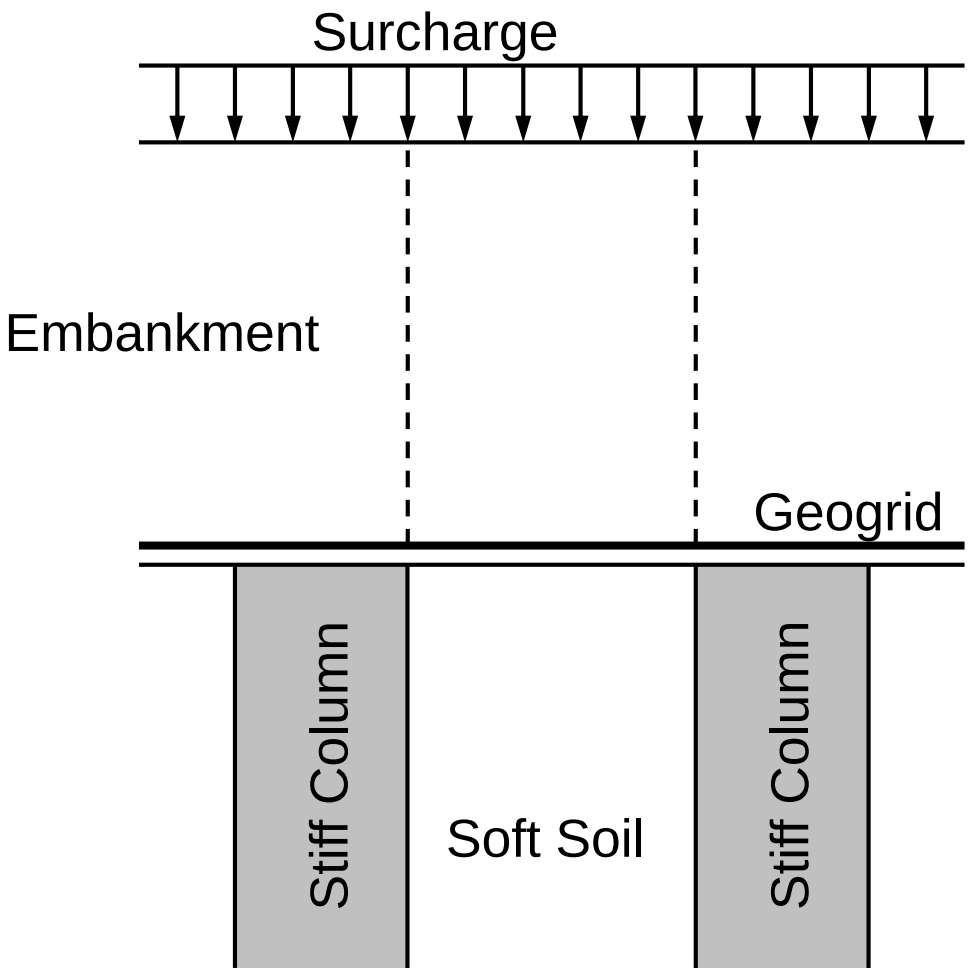

Surcharge Pressure, q
Embankment
H
$s_{col,geotop}$
$s_{soil,geotop}$
Geosynthetic Reinforcement
$s_{col,geobot}$
$s_{soil,geobot}$
Pile Cap
a
s

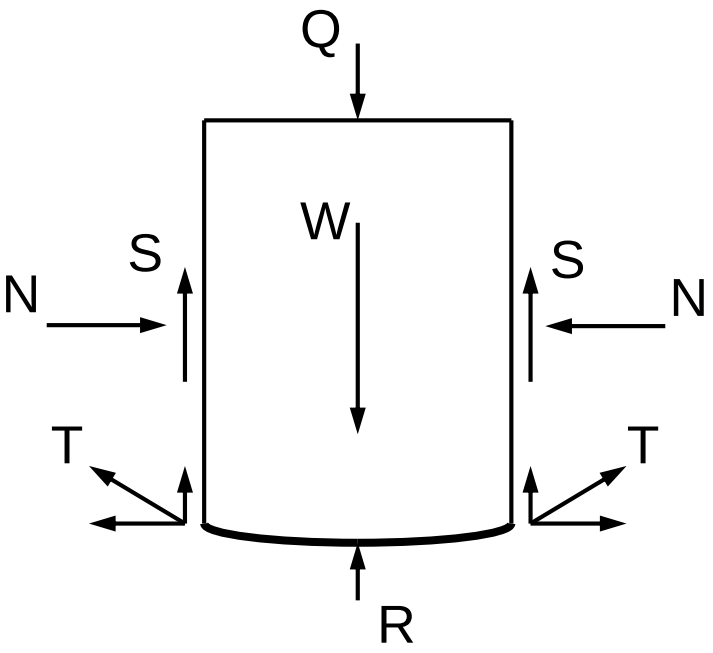
Vertical Equilibrium in Load-Displacement Compatibility Method



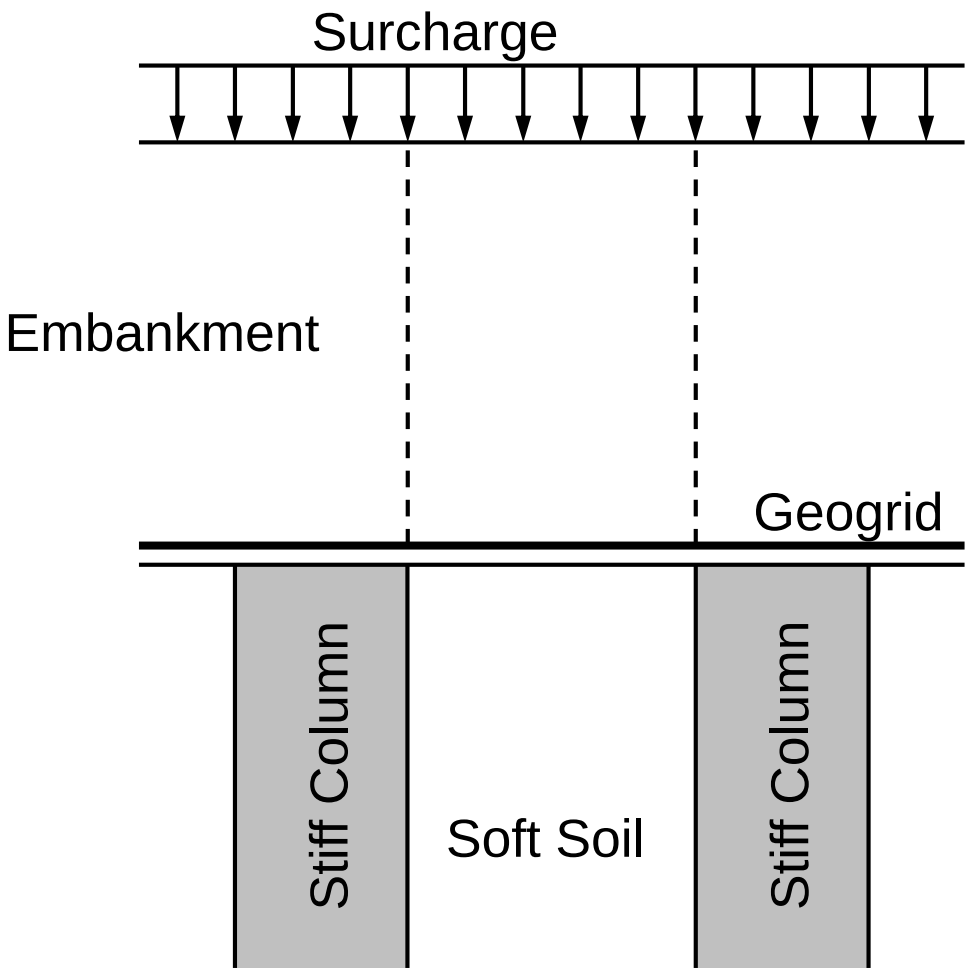


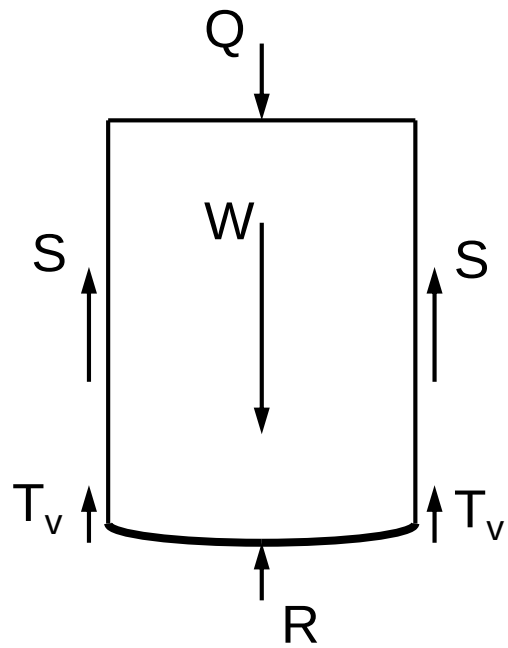
Vertical Equilibrium in Load-Displacement Compatibility Method



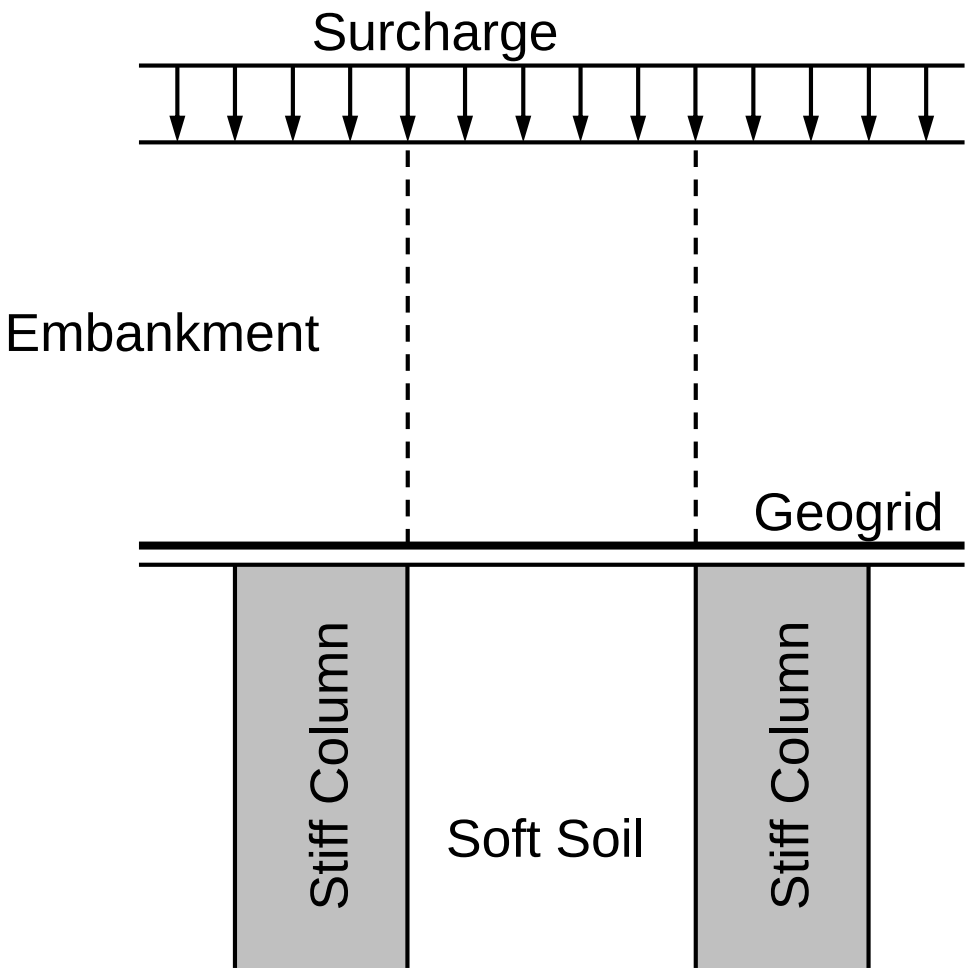


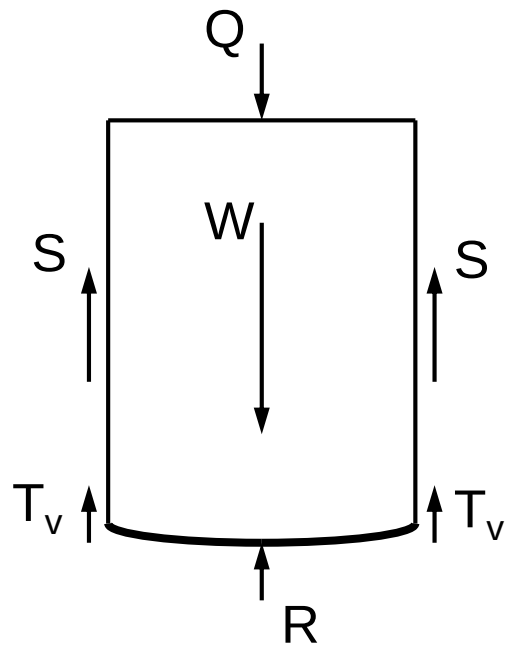
Vertical Equilibrium in Load-Displacement Compatibility Method





Vertical Equilibrium in Load-Displacement Compatibility Method



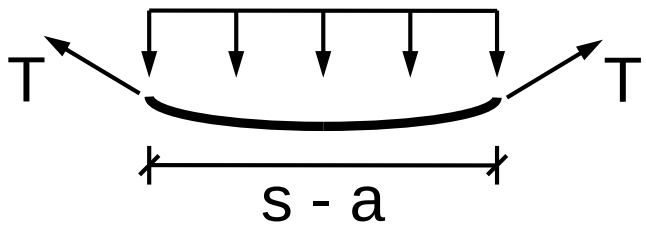


$$SRR_{net} = \frac{\left(W + Q - 2S - R\right)/A_{soil}}{gH + q}$$

$$= \frac{2T_v/A_{soil}}{gH + q}$$

Calculation of Geosynthetic Strain and Tension from SRR_{net} using Adapted BS 8006

$$p = SRR_{net}\left(\gamma H + q\right)$$



$$T = \frac{p(s^2 - a^2)}{4a}\sqrt{1 + \frac{1}{6\varepsilon}}$$

$$\varepsilon = \frac{T}{J}$$

- BS 8006:
- Parabolic deformation

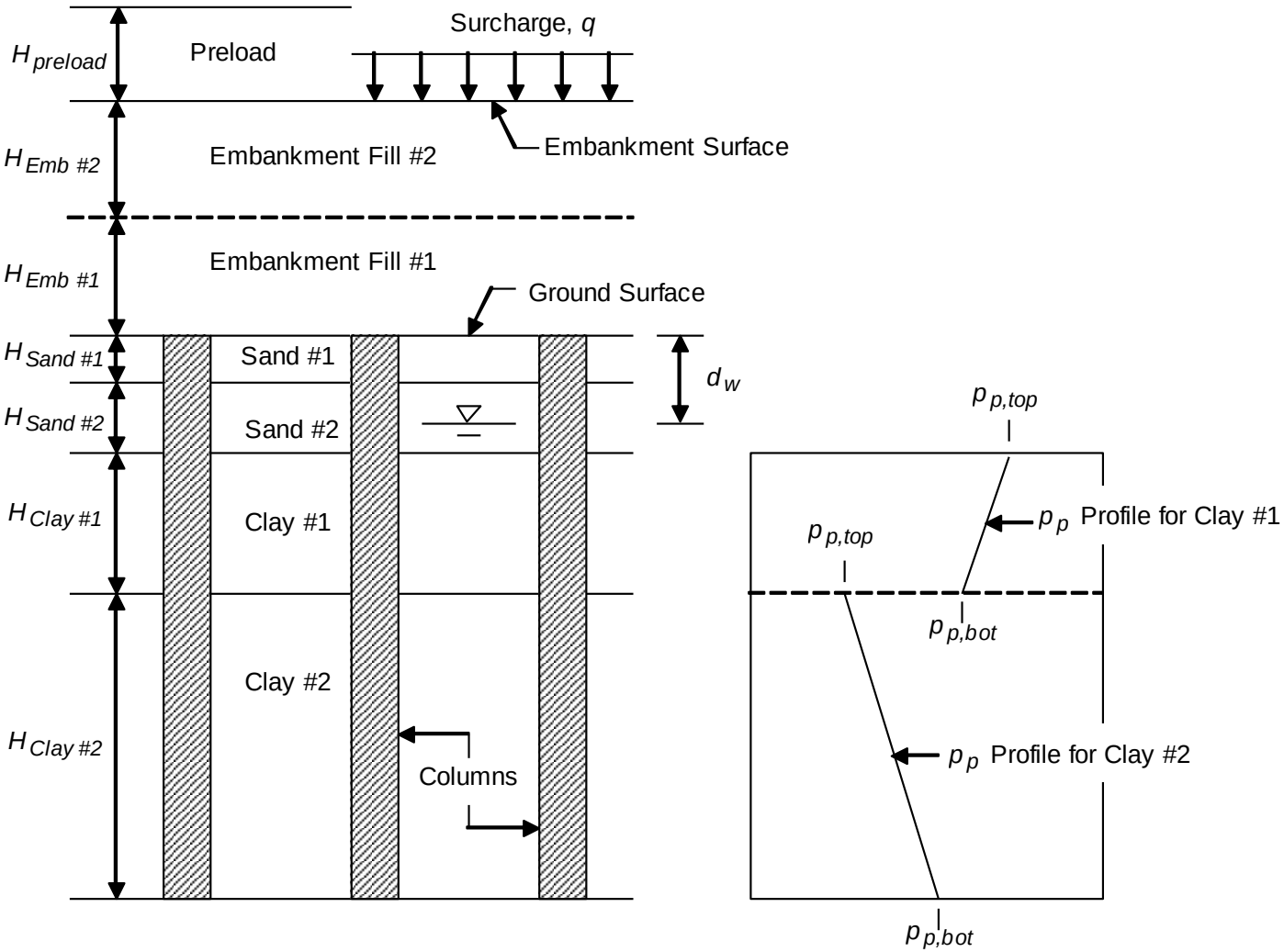
Settlement Analysis

- Settlement of Column based on stress on column and constant value of column modulus
- Settlement of soil is based on the stress on the soil and 1D compression of the clay using the compression ratio of the soil.

What are the parameters that you would like to be able to model in an analysis?

- Multiple soft soil layers
- A sand layer a subgrade
- Preloads and surcharges
- Column and Column caps
- Geosynthetic

Spreadsheet Solution



Spreadsheet Solution

GeogridBridge (Filz and Smith 2006)

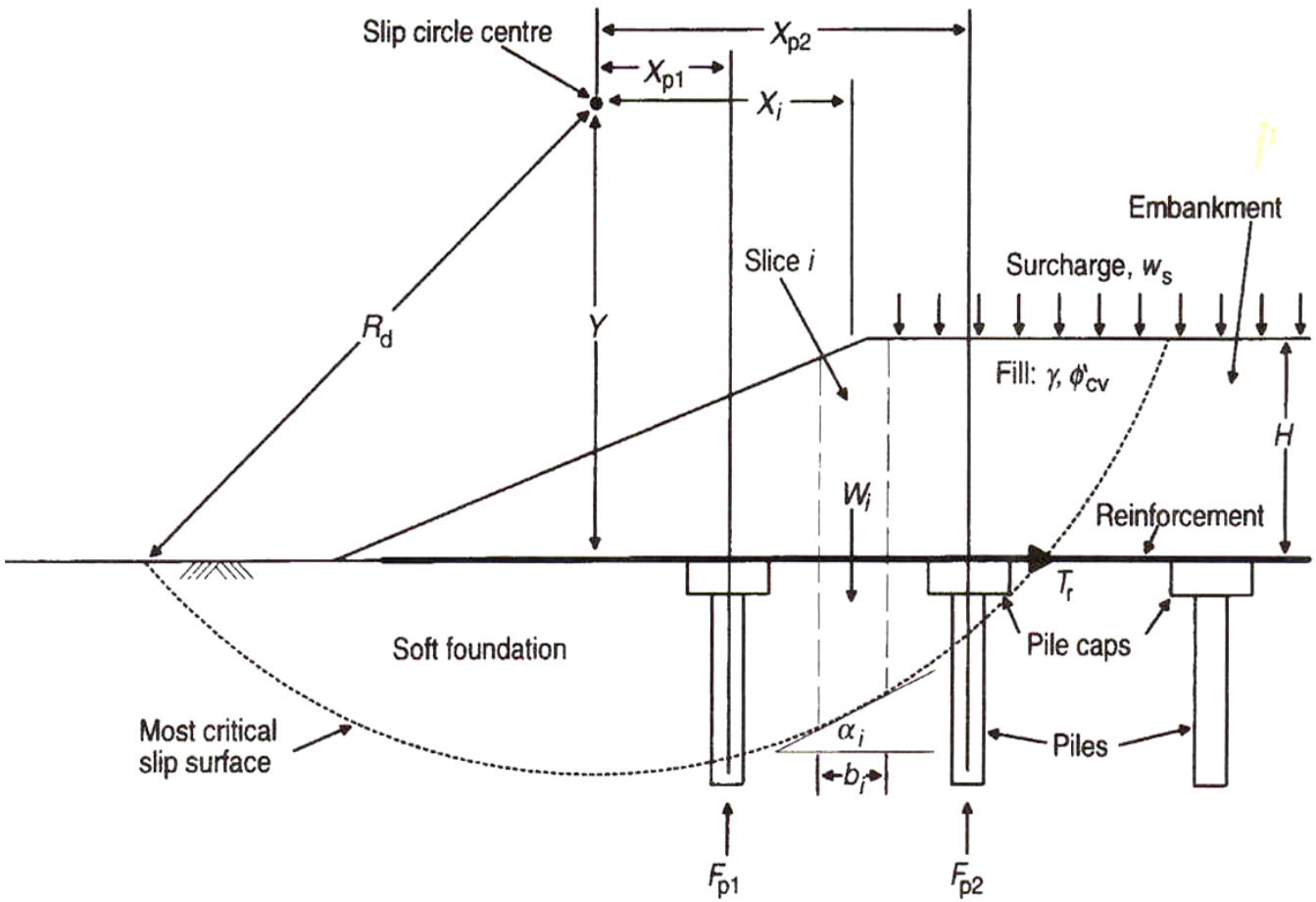
www.GeoTechTools.org.

What is the Reinforcement Total Design Load?

What direction is the lateral spreading load in?

What direction is the LTP load in?

LTP Design – Global Stability



Geosynthetic Properties – Limit State

$$LTDS = Tult/(RF_{CR} * RF_D * RF_{ID})$$

$$T_a = \text{Allowable Strength} = LTDS/FS$$

$$T_a = Tult/(RF_{CR} * RF_D * RF_{ID} * FS) \geq T_r$$

Reduction Factors

RF_{CR} = Creep Reduction Factor (range 1.6 –5.0)

RF_{D} = Durability Reduction Factor (range 1.1-2.0)

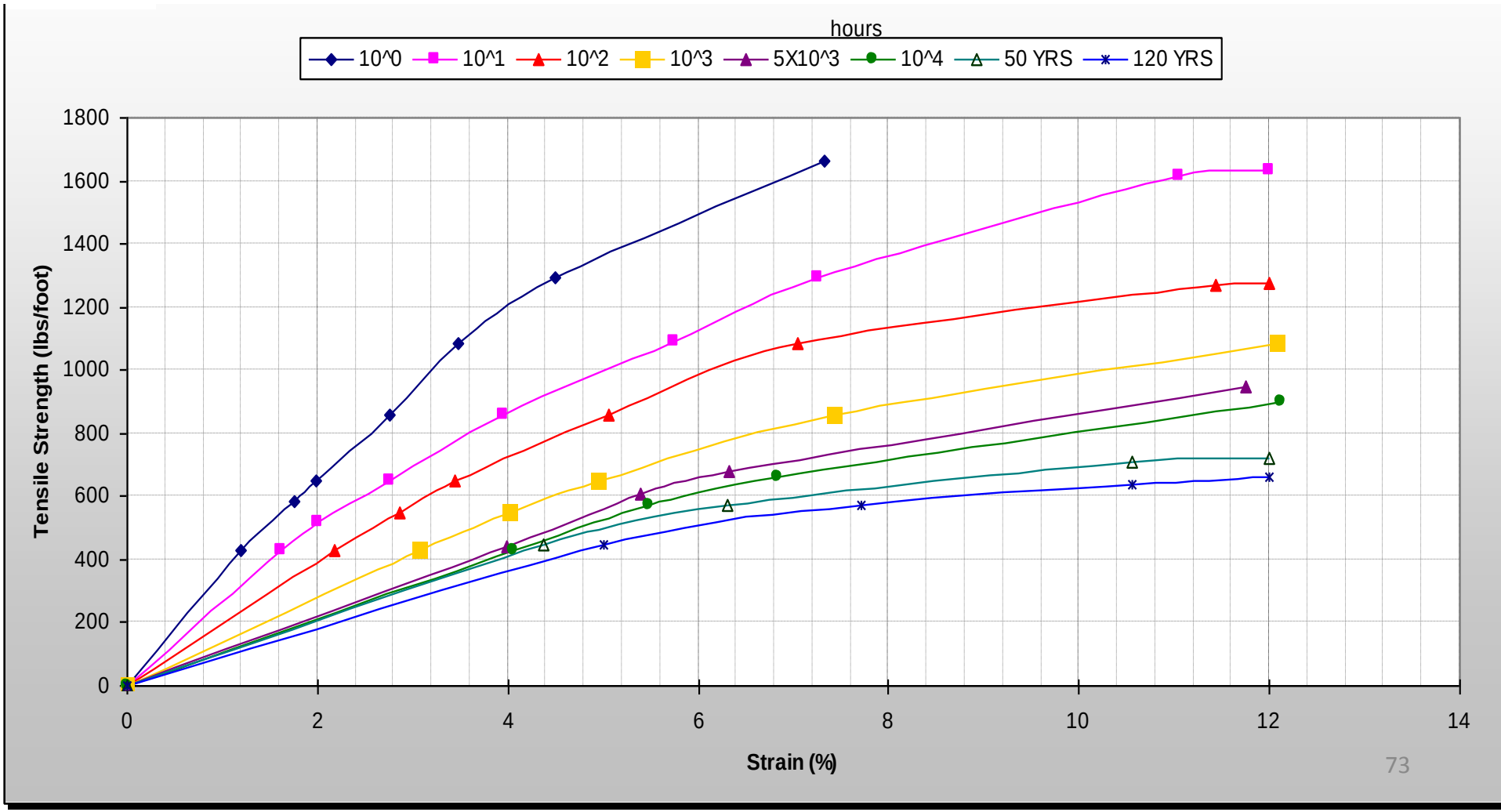
RF_{ID} = Installation Damage Reduction Factor (range 1.05-3.0)

FS = Factor of Safety (typically 1.5)

Geosynthetic Properties – Serviceability

$T_{cr@5\%\varepsilon} \geq T_r$ Beam

Geosynthetic Properties – Serviceability



Current FHWA Guidelines

- Check all limit states failure mechanisms
- Determine if LTP is required based on Filz Smith geogrid bridge analysis method
- If LTP is required, use the beam method to determine the geosynthetic requirements
- FEM method analysis results should not differ significantly from above recommended methods.

Questions