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Design of Aggregate Pier Groups to Control Settlement

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Outline of Presentation

- 1. Case History- (Mitchell & Huber, 1985)
- 2. Settlement of Large Group of
  Fully-Penetrating Columns
  Meaning of Unit-Cell Model
- 3. Significance of Load Test on Single Column
- 4. Relationship Between Single Column
  Response and Groups
- 5. Settlement of “Floating” Column Groups

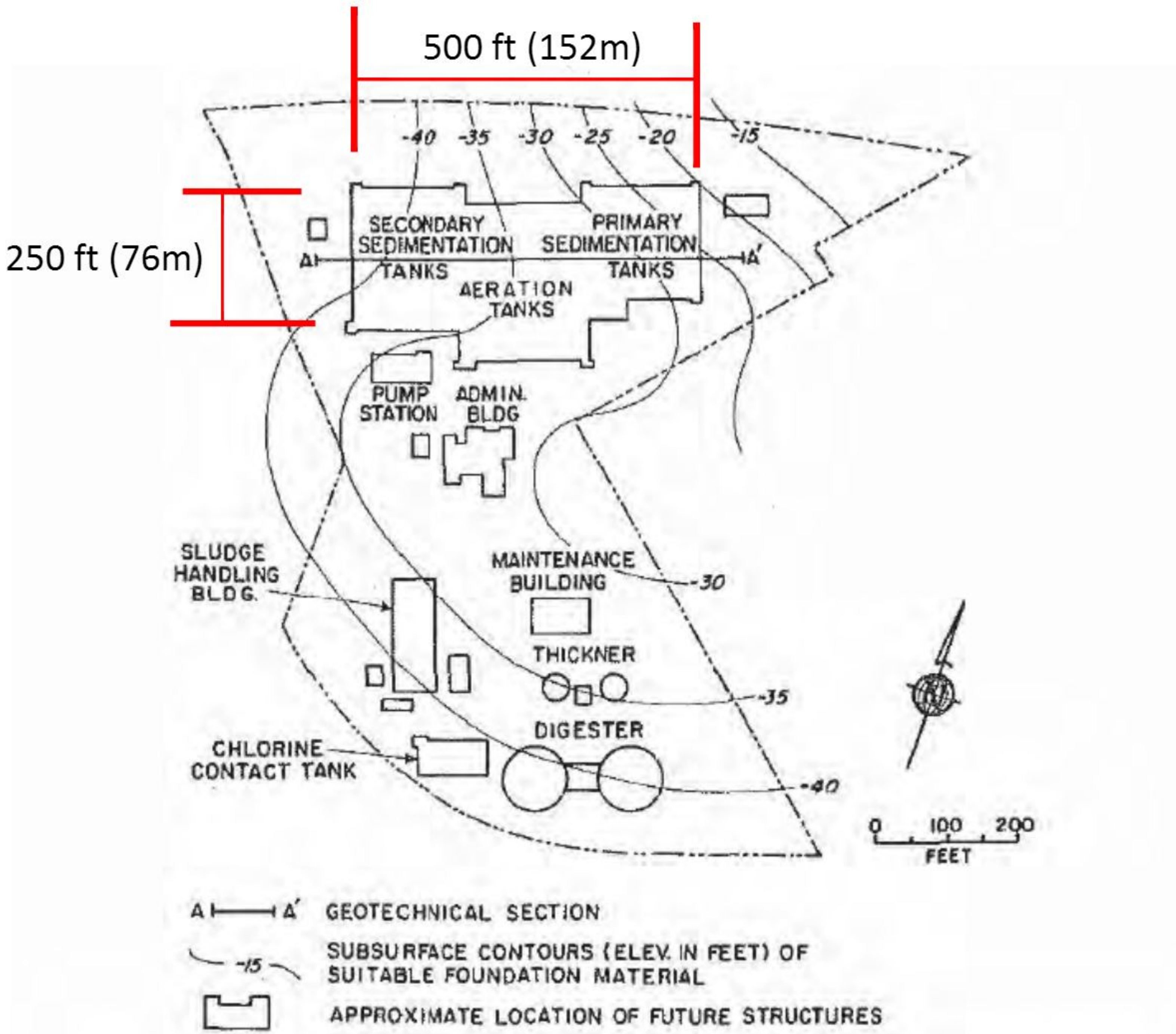


FIG. 1.—Site Plan—Santa Barbara Wastewater Treatment Plant

James K. Mitchell and Timothy R. Huber in 1985
published a paper in the ASCE Geotechnical Journal
"Performance of a Stone Column Foundation."

- Stone columns up to 48 ft in length.
- Foundation stresses were up to 3000 psf.
- The basic design: 30 tons (60 kips) per stone column with a settlement of less than 0.25 in.
- Column spacing ranged from 4ft x 5ft to 7ft x 7ft, with all columns extending completely through the soft deposits.
- Numerical analysis was performed for a 5.75 ft by 5.75 ft spacing with a 3.5 ft diameter column 40 ft long, thus producing an **area replacement ratio of 29%.**

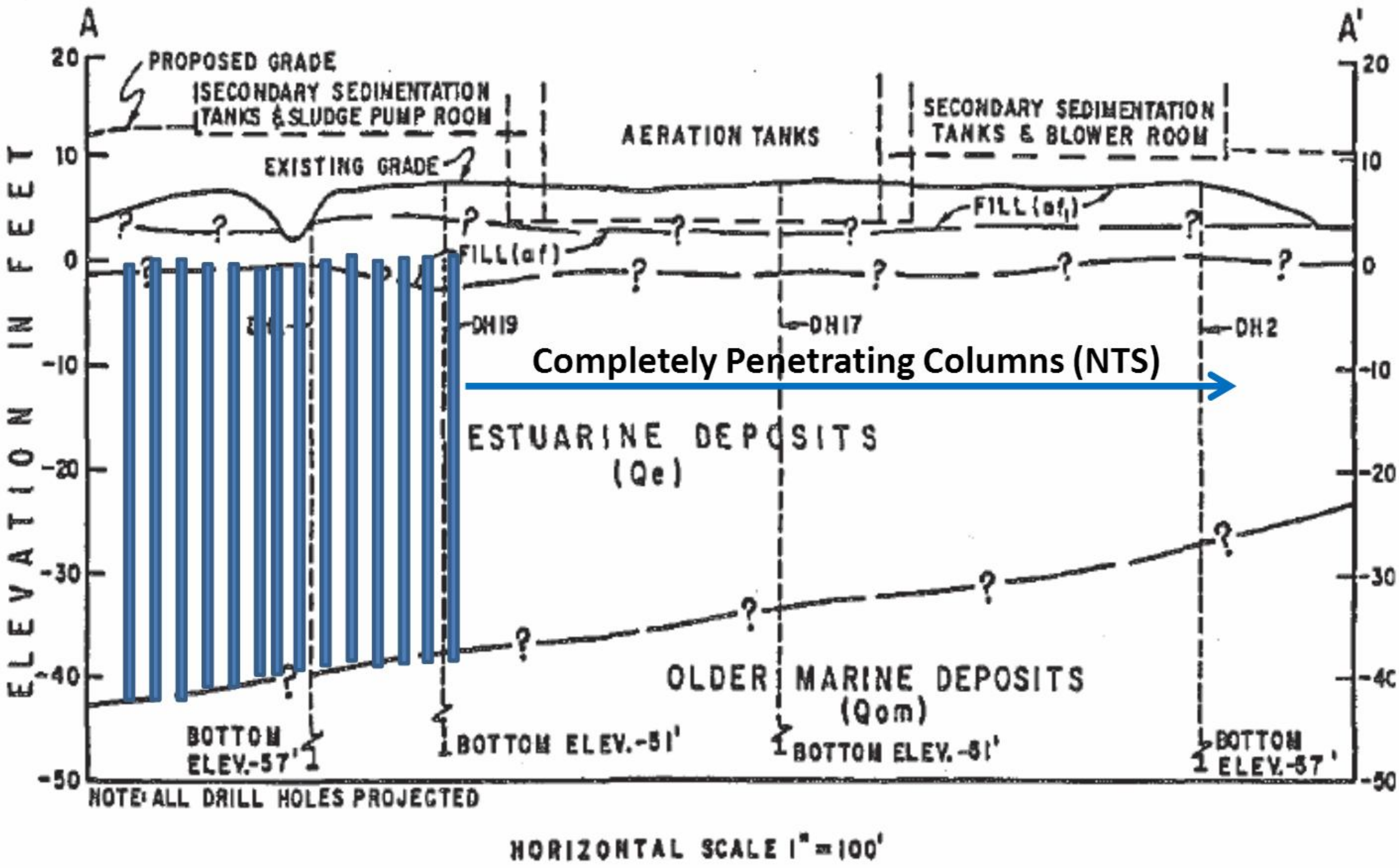


FIG. 2.—Soil Conditions Beneath Biological Units Structure

GEOLOGIC CLASSIFICATION	DEPTH (ft.)(m.)	ENGINEERING CLASSIFICATION	MOISTURE CONTENT (%)	DRY DENSITY (lb./cu.ft.)	SPT "N"
RECENT FILL	0	CLAYEY SAND (SC)			
		SANDY SILT (ML)			
ESTUARINE DEPOSITS	10	SILTY SAND (SM)	21	95	9
	-5	SILTY CLAY (CL) AND CLAYEY SILT (ML)	48	70	3
	20	SANDY SILT (ML)	33	85	6
		CLAYEY SAND (SC)	52	49	6
		SANDY SILT (ML) AND SILTY CLAY (CL)			
	30 -10	SILTY SAND (SM) INTERLAYERED WITH CLAYEY SAND (SC) AND SANDY CLAY (CL)	28 21	84 97	23 19
OLDER MARINE DEPOSITS	40	SANDY CLAY (CL)	23	106	
		SILTY SAND (SM INTERLAYERED WITH CLAYEY SAND (SC) AND CLAYEY SILT (ML)			
	-15 50	CLAYEY SAND (SC)	25	105	

FIG. 3.—Typical Soil Profile

28 single-column loads tests (of 6,500 stone columns).

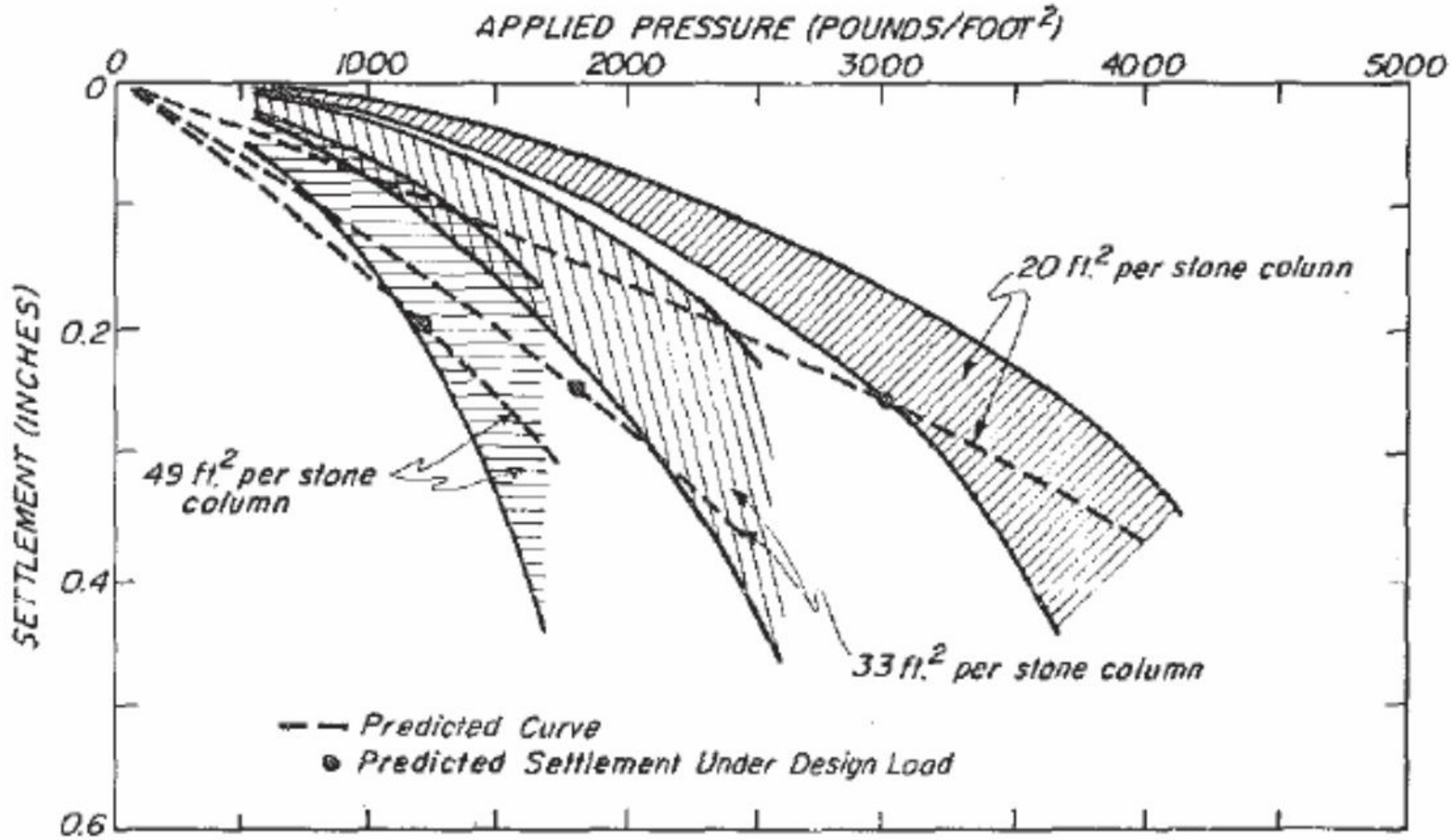
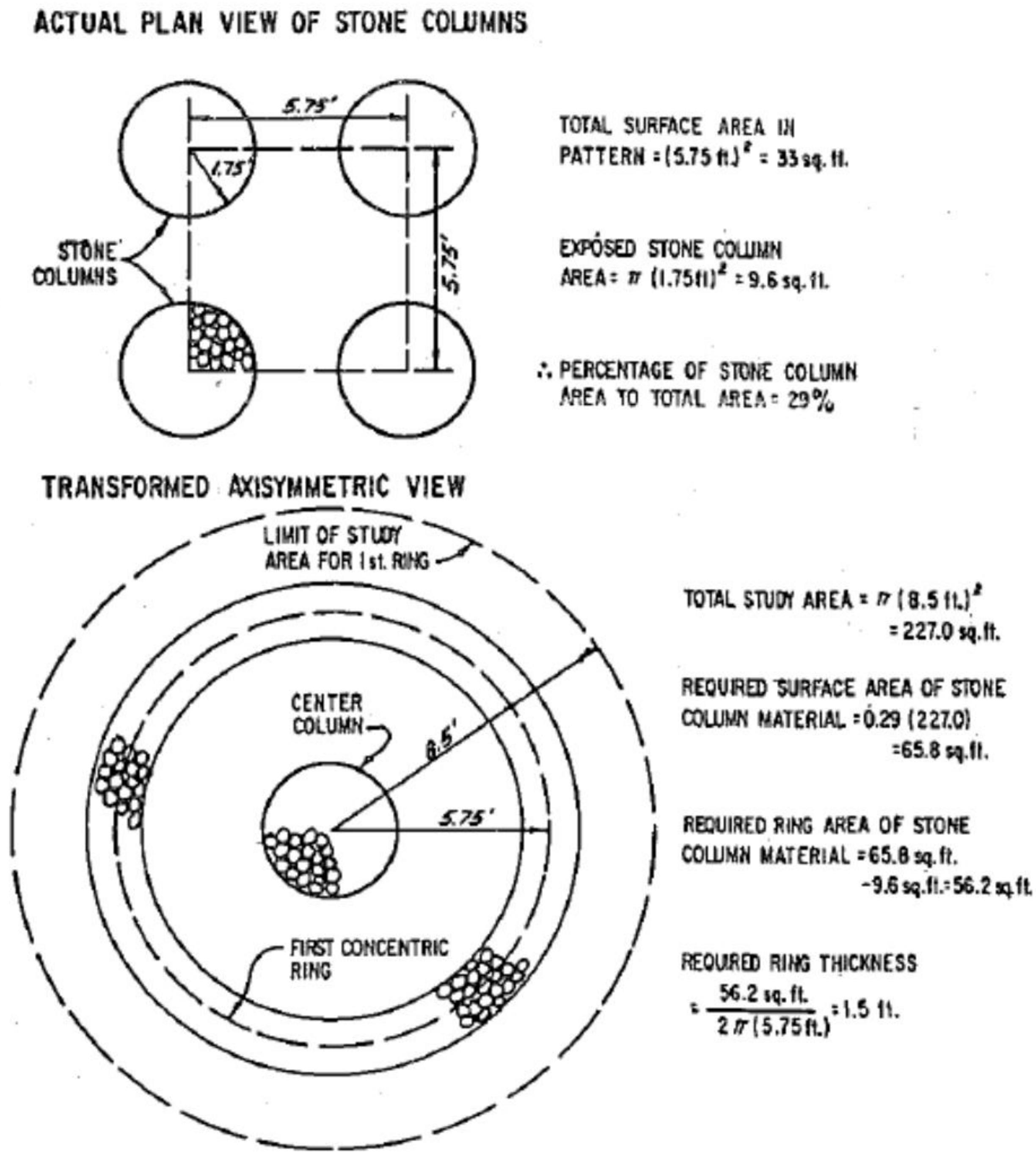
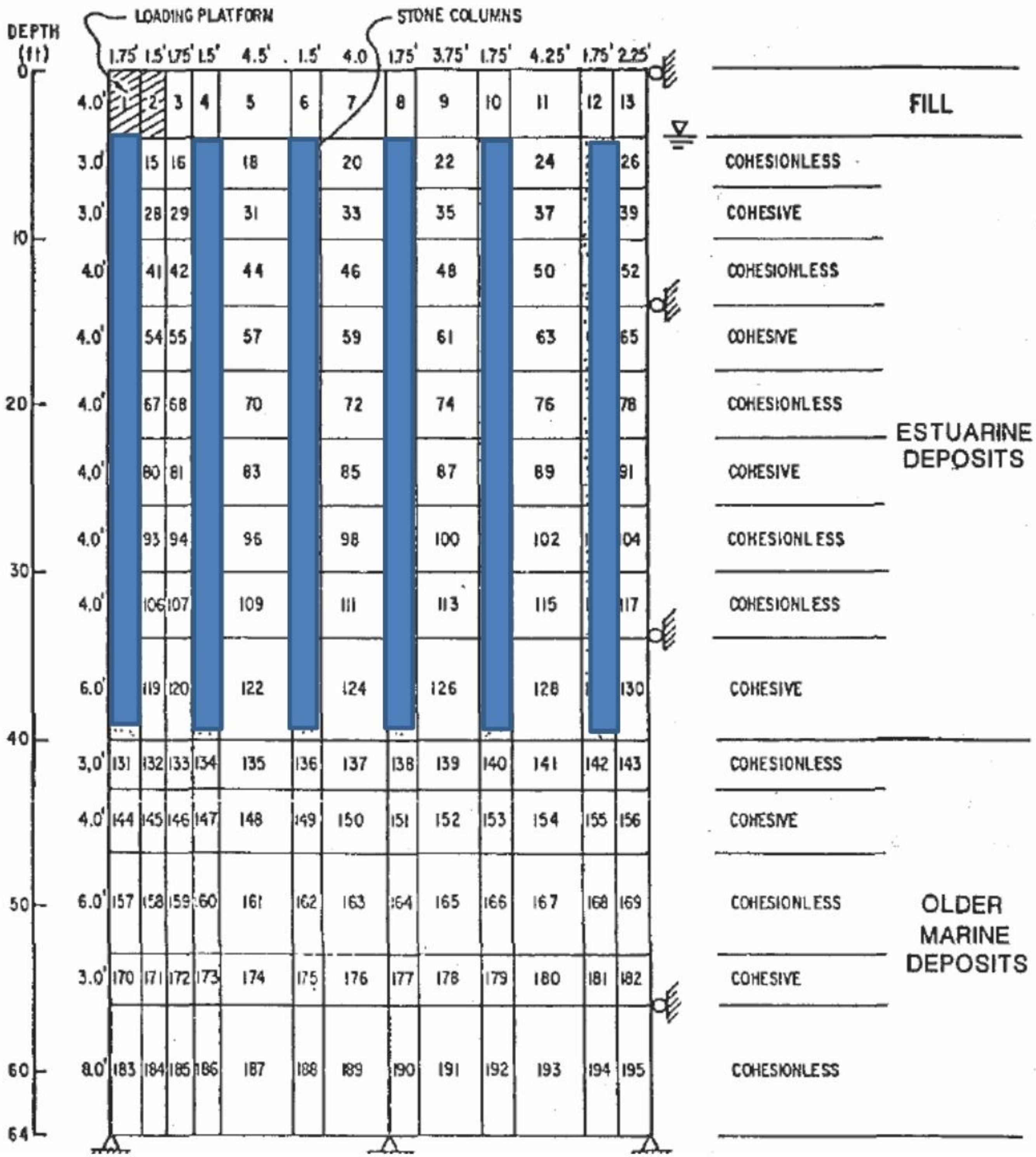


FIG. 8.—Comparison of Measured and Predicted Load-Settlement Behavior of a Single Loaded Stone Column Within a Group

Determination of Axisymmetric Model Geometry





LOADING PLATFORM
STONE COLUMNS
DEPTH (ft)
FILL
COHESIONLESS
COHESIVE
ESTUARINE DEPOSITS
OLDER MARINE DEPOSITS

130% Increase of Column Stiffness reduced Settlement by 10%

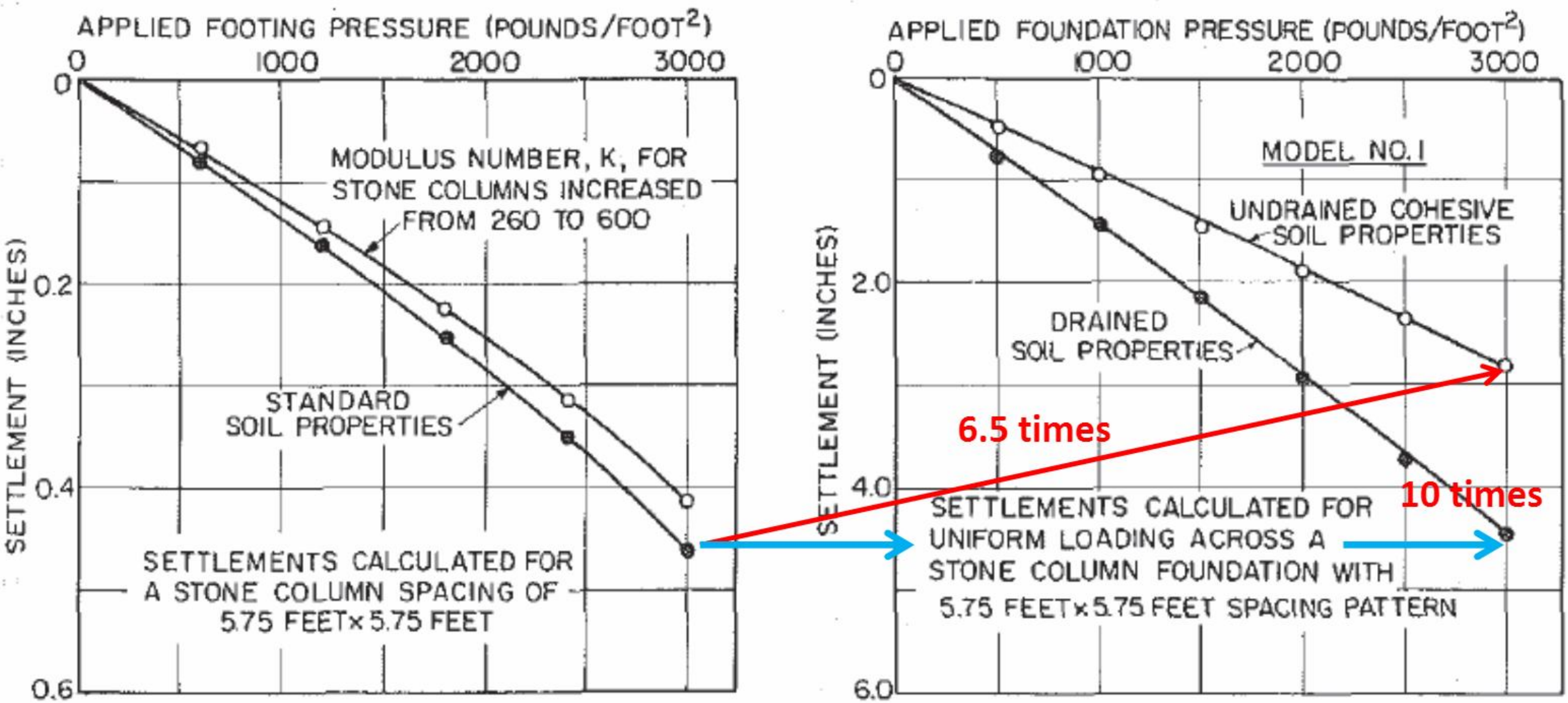


FIG. 10.—Effect of Decreased Stone Column Stiffness on Load-Settlement Behavior of a Single Loaded Stone Column in a Group

FIG. 11.—Predicted Load-Settlement Curves for Uniform Loading of a Large Area Stabilized With Stone Columns

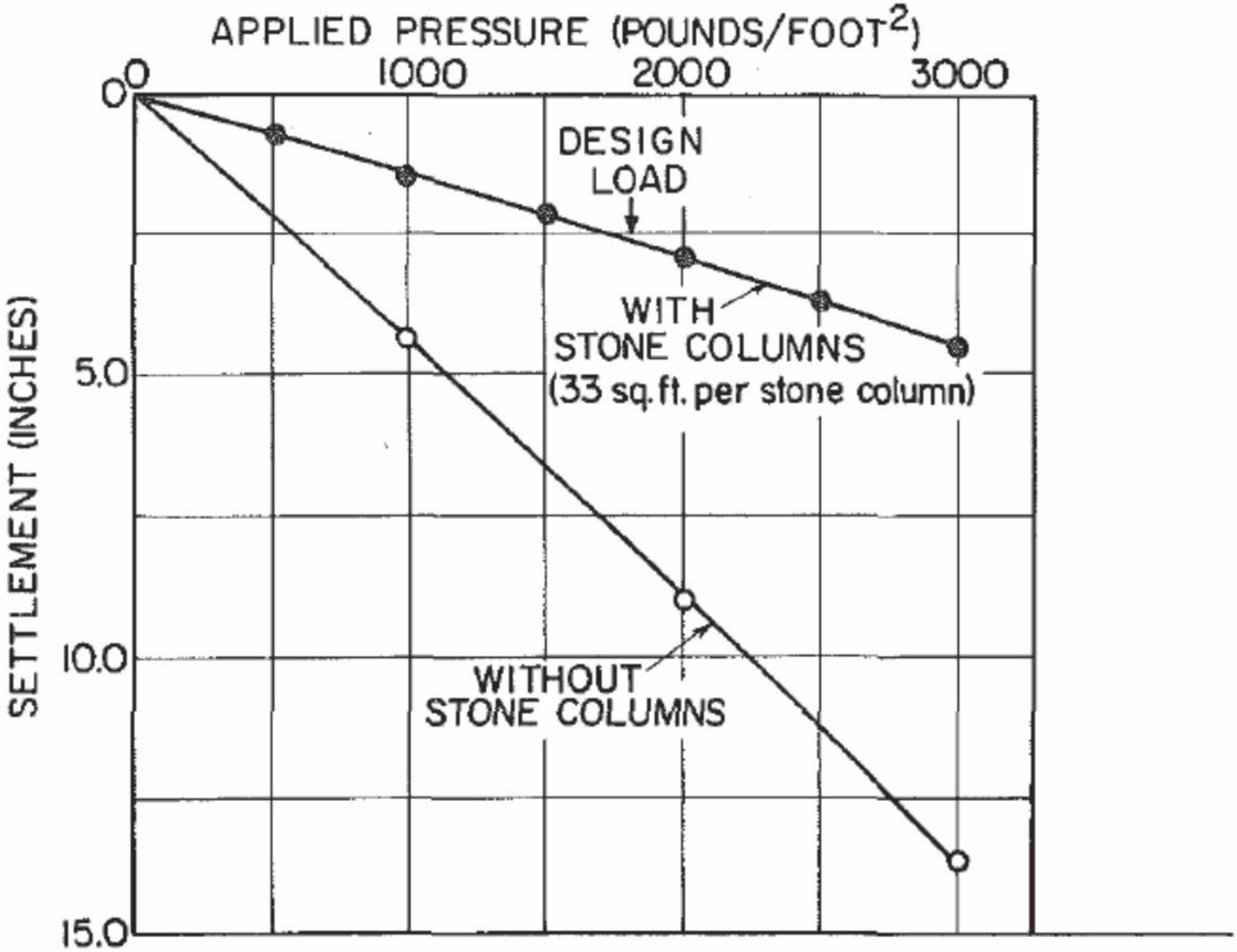


FIG. 12.—Predicted Foundation Settlements With and Without Stone Columns

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- 1. Case History- (Mitchell & Huber, 1985)
- 2. **Settlement of Large Group of Fully-Penetrating Columns**
  Meaning of Unit-Cell Model
- 3. Significance of Load Test on Single Column
- 4. Relationship Between Single Column Response and Groups
- 5. Settlement of "Floating" Column Groups

Settlement of Footings supported by Aggregate Piers

- **Objective**: Decrease settlement of profile into which columns are placed.

- The total ground-surface settlement is potentially made up of two parts:
  - **1) compression of the reinforced zone**, and
  - 2) compression of the zone beneath the columns.

Reinforced-Zone Compression

(Fig. from **Poorooshasb and Meyerhof, 1997**)

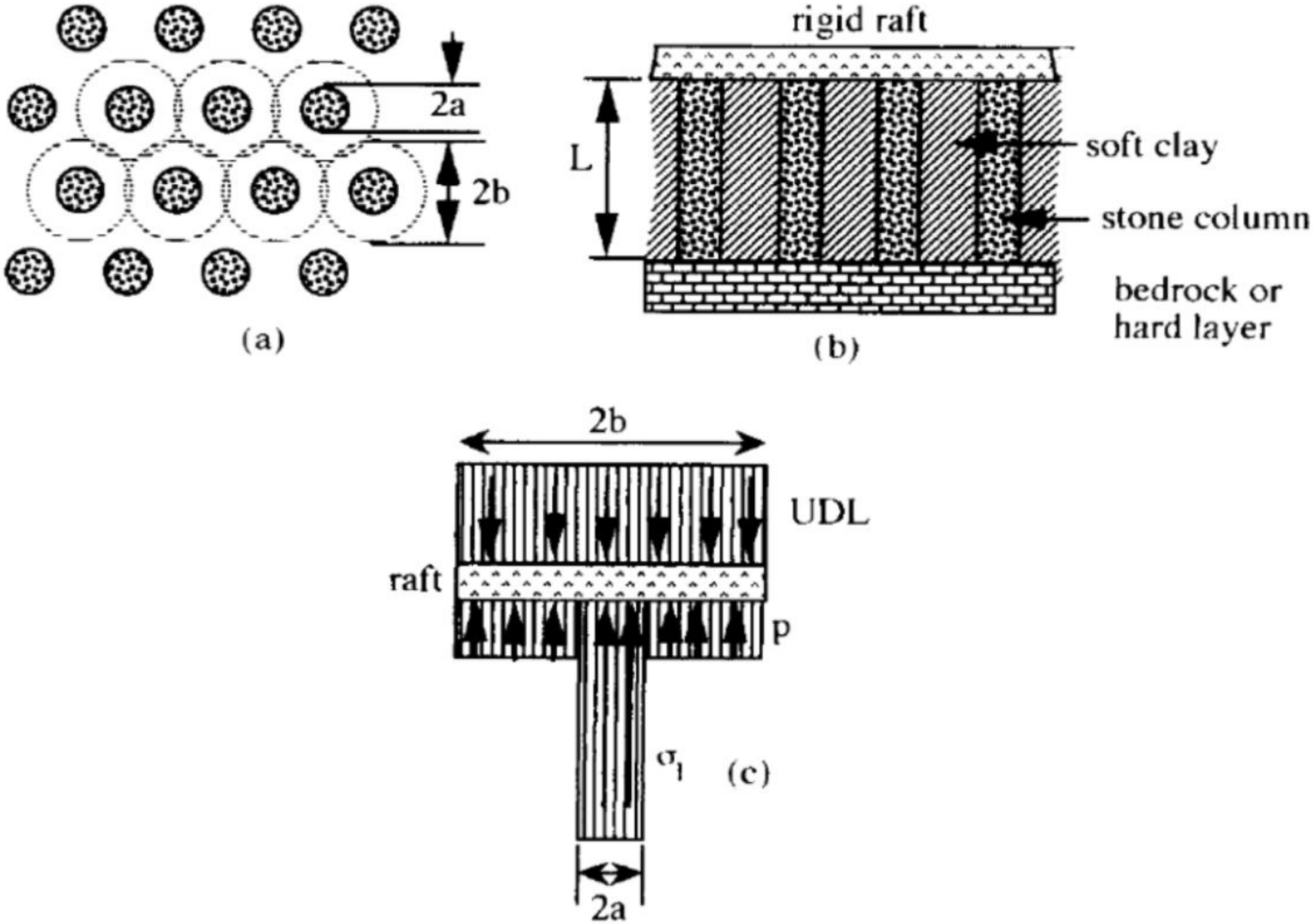


Fig. 1. Key figure, $2a$ = column diameter, $2b$ = spacing.

Mitchell and Huber, 1985 (cont.)

- **Measured settlements about 30-40% of the values expected from unimproved ground [Sobserved = 0.3-0.4 x Spredicted w/o columns].**
- The settlement of a large uniformly loaded area of improved ground was predicted to be about **ten times** that measured in a load test on a single stone column within the area.
- Measured settlements varied from 1.0-2.4 in. for soft sediment thicknesses of 32-35 ft.
- A settlement of 2.5 in. was predicted by the finite element analysis. Settlement predictions using other, simpler methods gave values which agreed reasonably with both the measured values and the finite element predictions.

Mitchell and Huber, 1985 (cont.)

- Mitchell and Huber summarize their findings that the prediction of settlements for a stone column foundation supporting a large loaded area and fully penetrating the compressible layer can be made by a variety of methods:
  - Experience-Based Methods
  - Elastic Theory
  - Reduced Stress Methods

Mitchell and Huber, 1985 (cont.)

- **Experience-Based Methods:**
  - (Greenwood, and Kirsch, 1983) A settlement reduction to about **30% of the untreated ground.**
  - Engelhardt: Predicted settlement of large-loaded area should be **about 10 times greater than that measured under the design load in a single-column test**. As the single-column load test settlements were limited to 0.25 in., a settlement of 2.5 in. would be predicted.

Mitchell and Huber, 1985 (cont.)

- **Elastic Theory**
  - The method proposed by Poulos (1972) led to the prediction that the settlement of a large loaded area should be about **5 to 10 times greater than that of a loaded single column** in a group. When applied to single column load test results, this gave values of 1.2-2.5 in.

Mitchell and Huber, 1985 (cont.)

- **Reduced Stress Methods**
  - Priebe (1976). Application of this method yielded $\mathbf{S_{treated} = 0.4 * S_{untreated}}$
  - Abooshi et al. (1974). Application of this method yielded $\mathbf{S_{treated} = 0.4 - 0.5 * S_{untreated}}$ depending on the column spacing.

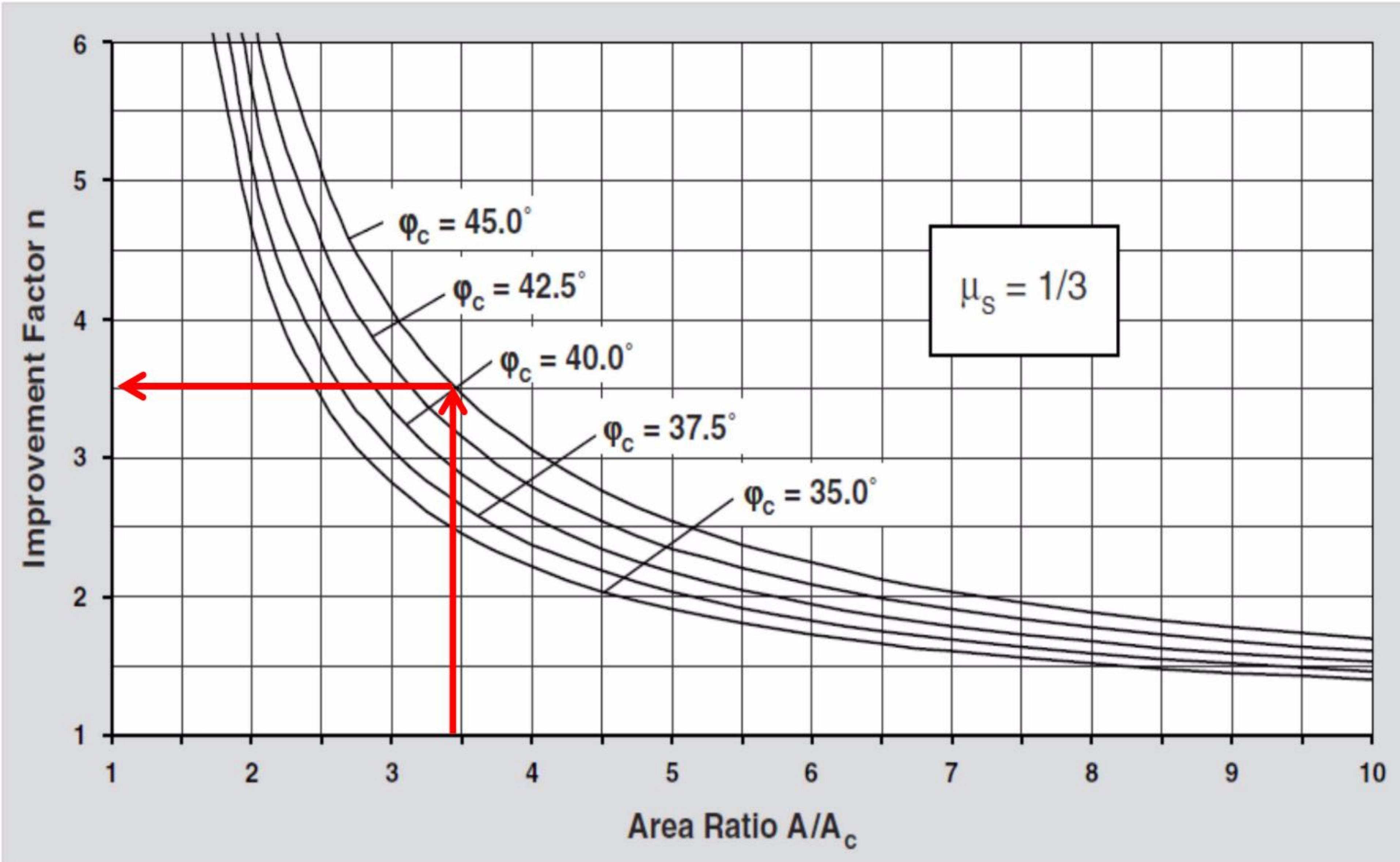


Figure 1: Design chart for vibro replacement

$A/A_c = 1/ARR \quad (1/0.29 = 3.45)$

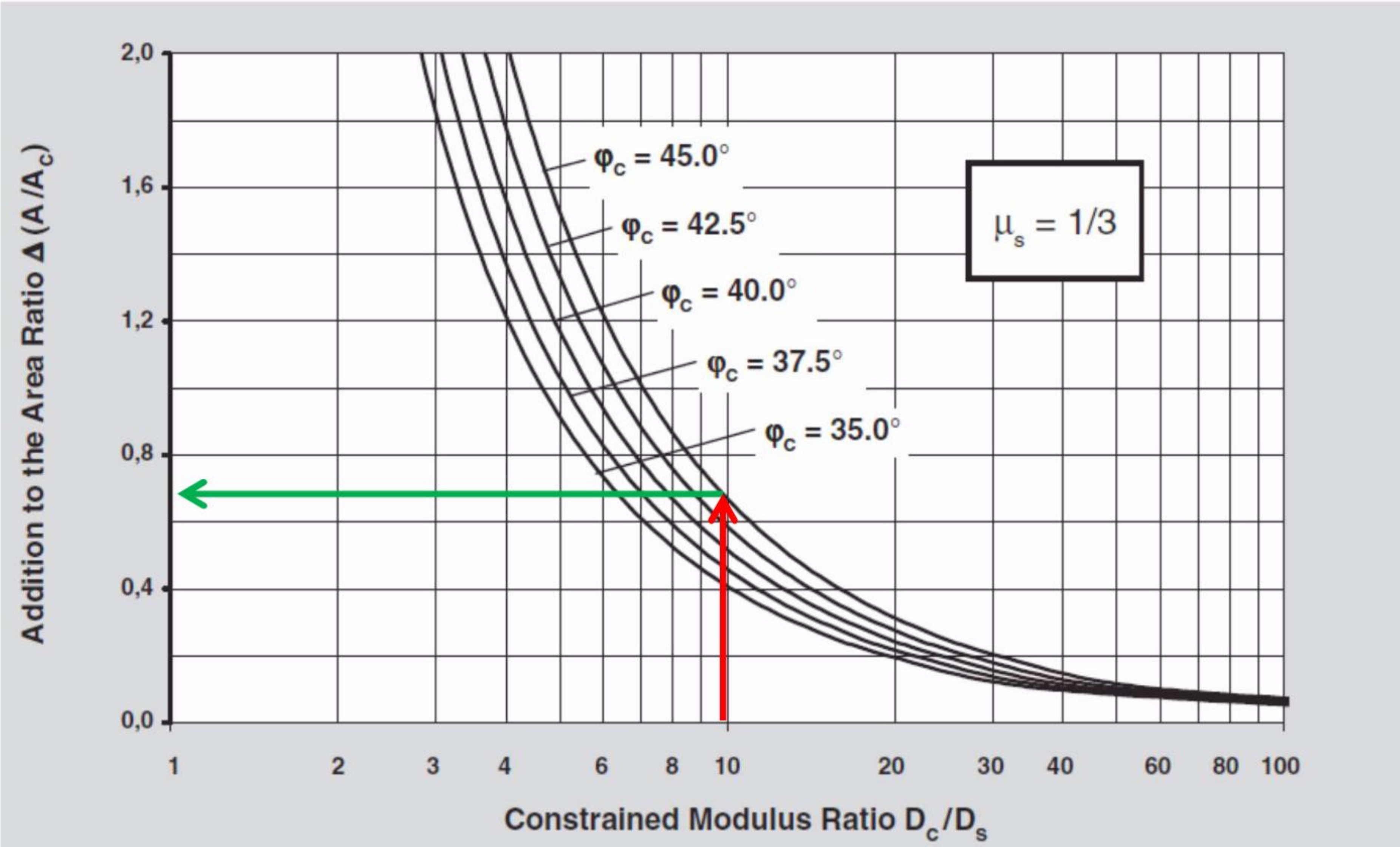


Figure 2: Consideration of column compressibility

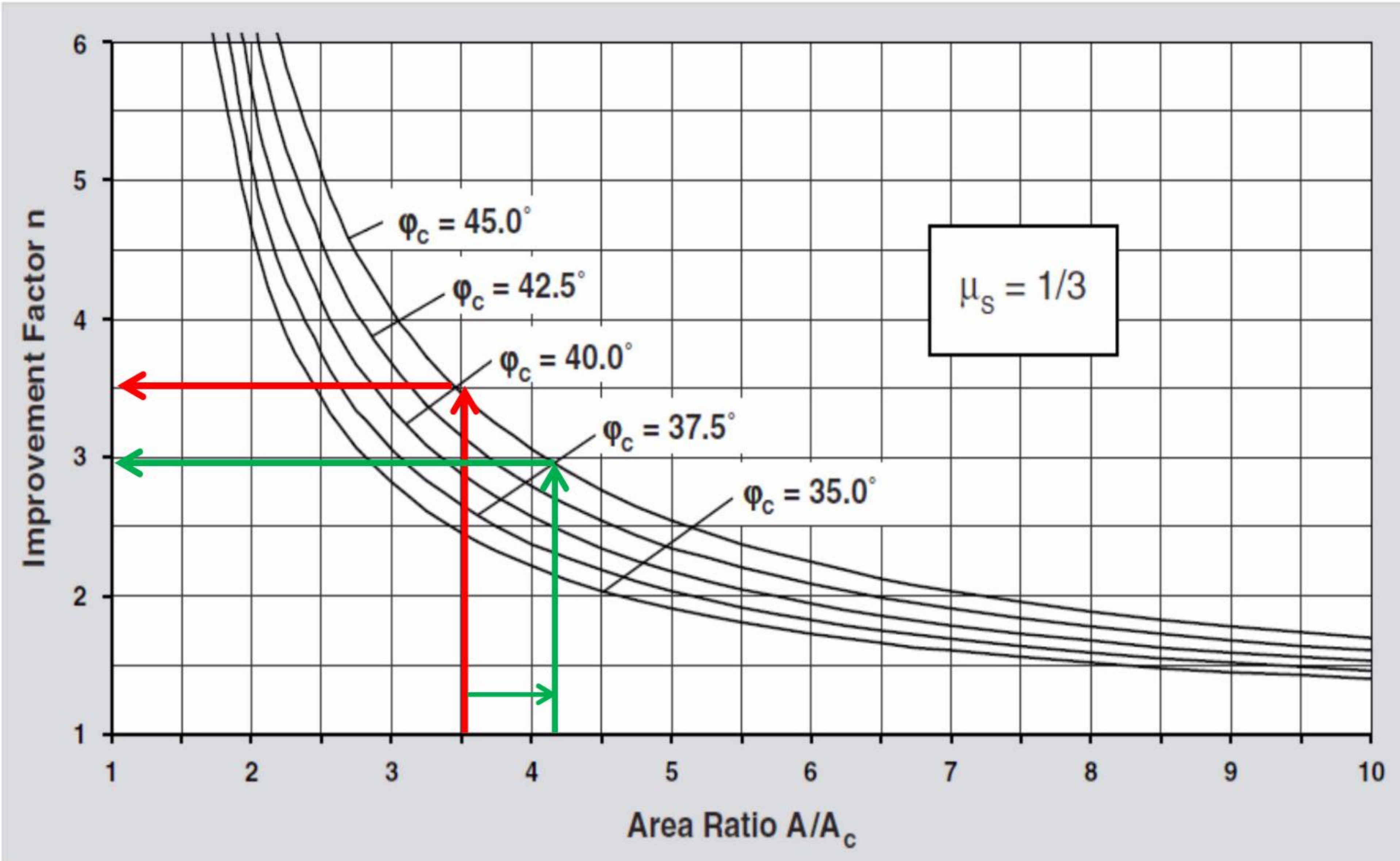


Figure 1: Design chart for vibro replacement

So, S(reinf) = S(unreinf) / 3

H.B. Poorooshasb and G.G. Meyerhof in 1997 in
Computers and Geotechniques published a paper,
"Analysis and Design of Stone Columns and Lime Columns."

- **They explored**: The **efficiency of end-bearing stone columns**…in reducing the settlement of a foundation system… and explored the influence of factors including:
  - Column spacing
  - Soil properties into which the columns are placed
  - Properties of the column material
  - Insitu stresses
  - Length of the columns to the incompressible base layer (end bearing), and
  - The magnitude of the surface load (expressed as a uniformly distributed load at the base of the foundation (UDL).

Poorooshasb and Meyerhof, 1997

- **They note**: "Short columns installed in a deep layer of soft soil deposit will not be effective in reducing the settlement of the foundation system. It is the objective of this paper to evaluate the influence of the various factors involved and thus arrive at a practical design procedure." (p49)
- From Priebe (1975) they note:
- $n = \frac{\left(\frac{ULD}{E_S}\right)}{\left(\frac{\delta}{L}\right)} = 1 + A_r \left(\frac{E_c}{E_s} - 1\right)$
- Where n = settlement ratio and A_r = area ratio (or area replacement ratio, A_c/A).

- $n = \frac{\left(\frac{ULD}{E_S}\right)}{\left(\frac{\delta}{L}\right)} = 1 + A_r \left(\frac{E_C}{E_S} - 1\right)$

- So, if one assumed Ec = 900 ksf and Es = 100 ksf:

  for A_r (or Ac/A) = 0.3, the value of n would be:

- $n = 1 + 0.3\left(\frac{900}{100} - 1\right) = 3.4$ and $1/n = 0.29$

- if $A_r = 0.2$ then $n = 2.6$ and $1/n = 0.38$

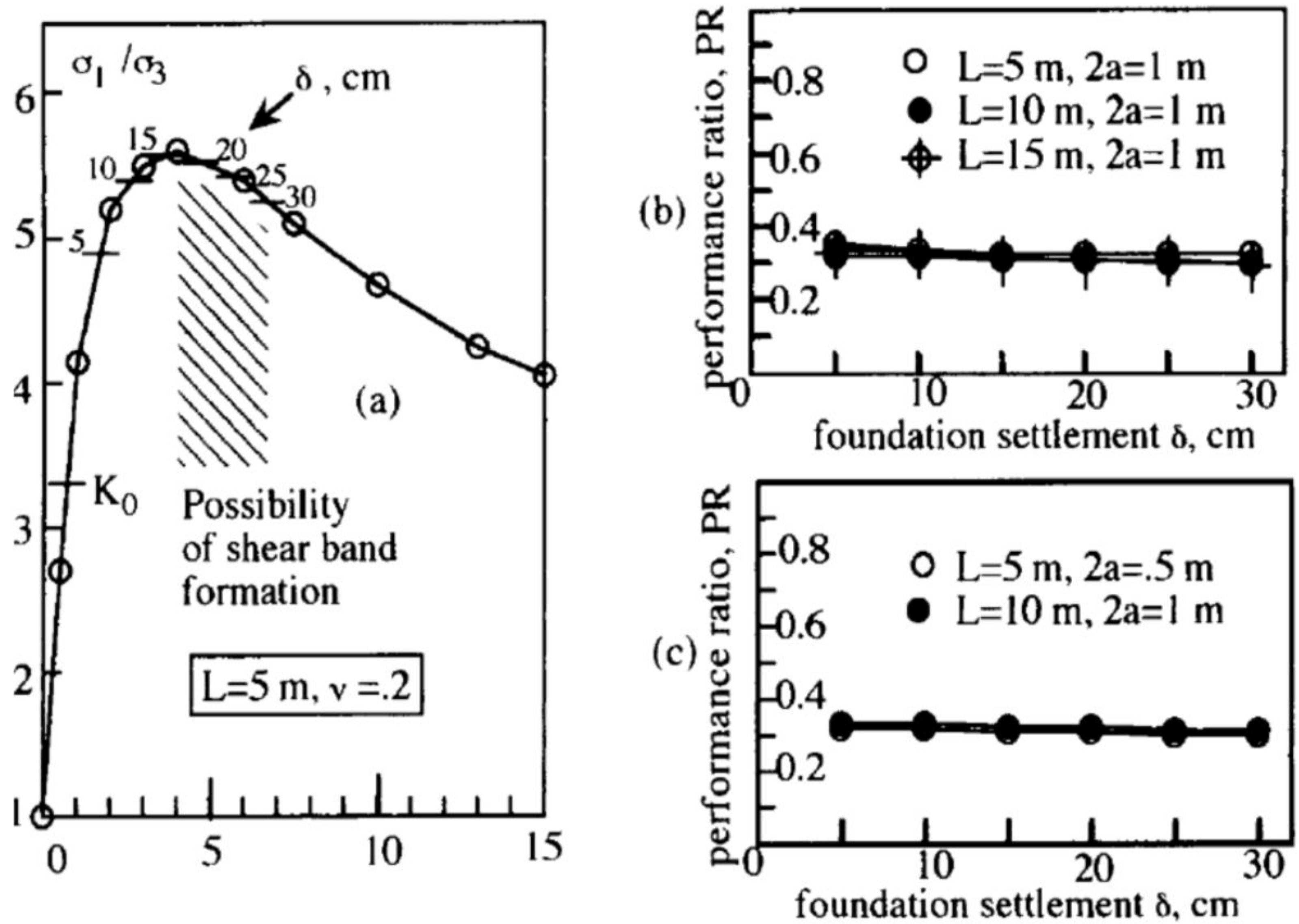


Fig. 4. Effect of column length on the performance ratio.

Poorooshasb and Meyerhof, 1997 (cont)

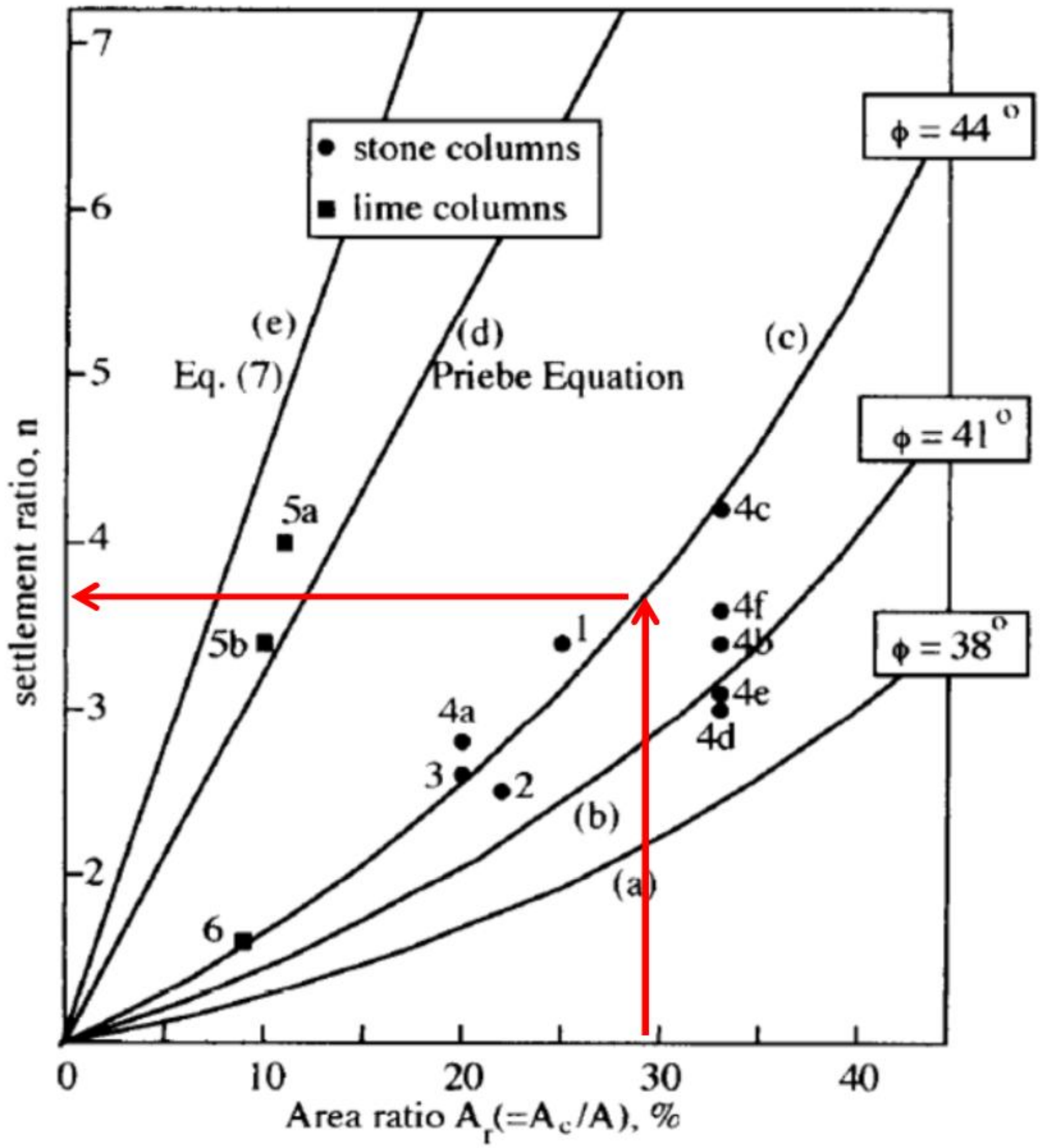
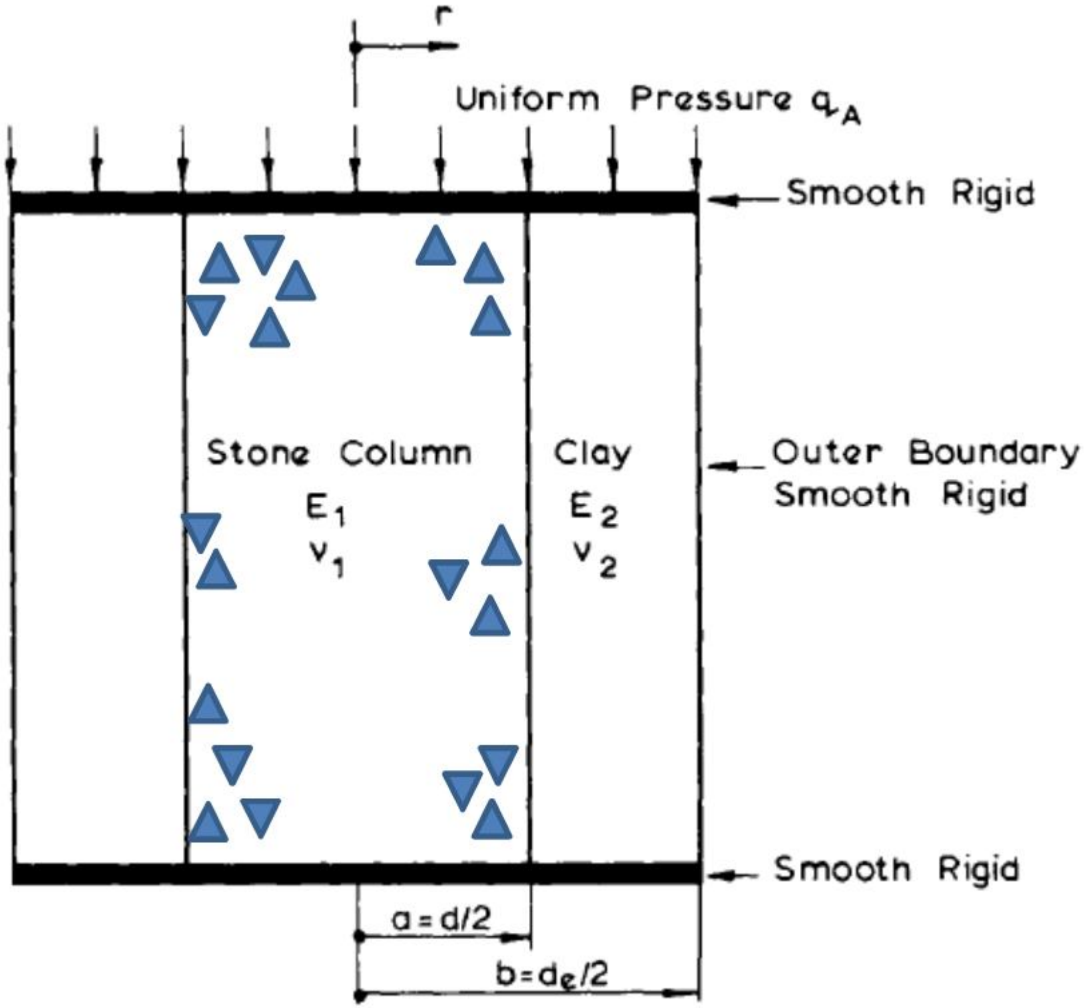


Fig. 7. Settlement ratio vs area ratio for stone columns and lime columns. Comparison of analytical results with field data.

Meaning of Unit Cell



(from Balaam and Booker, 1981)

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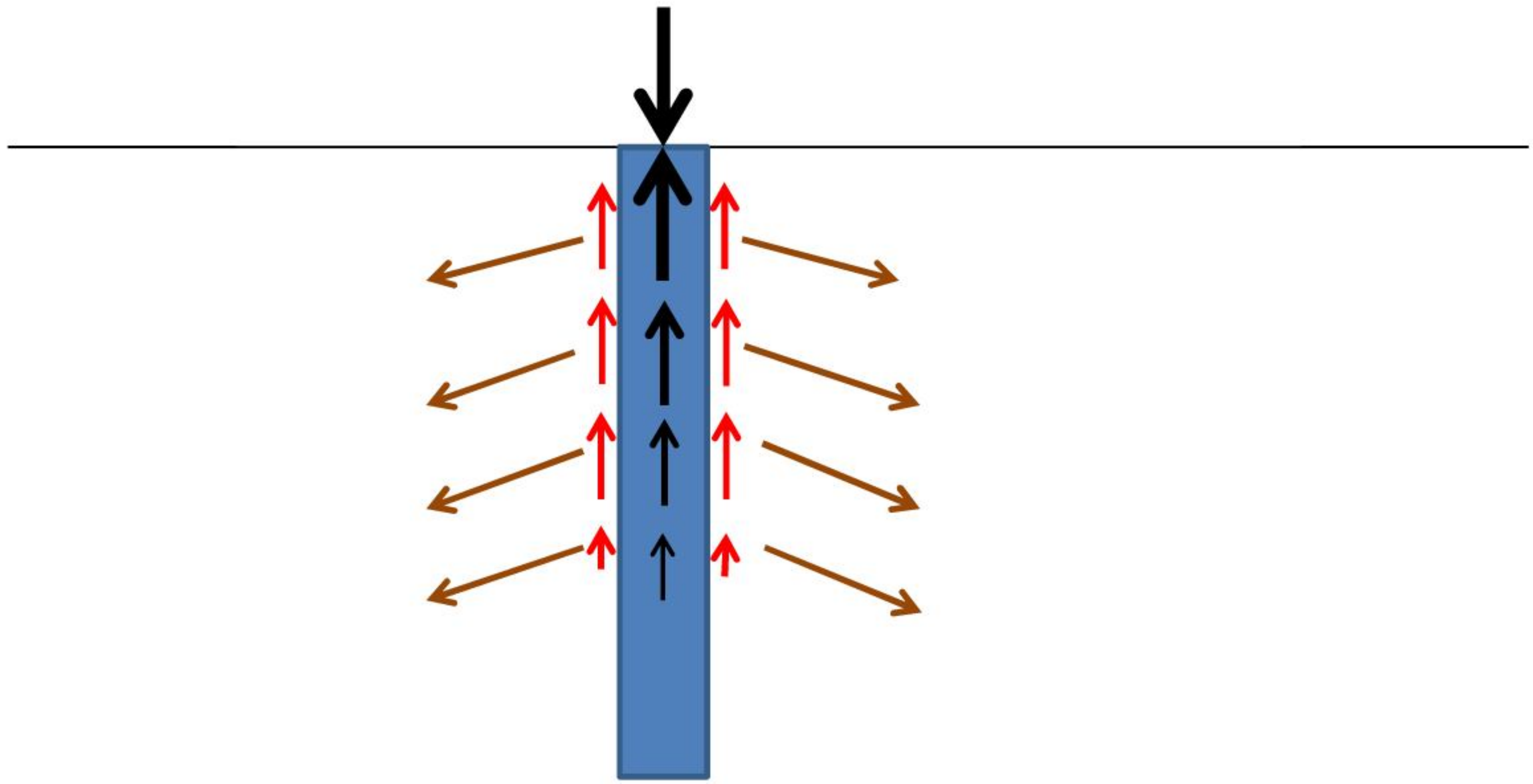
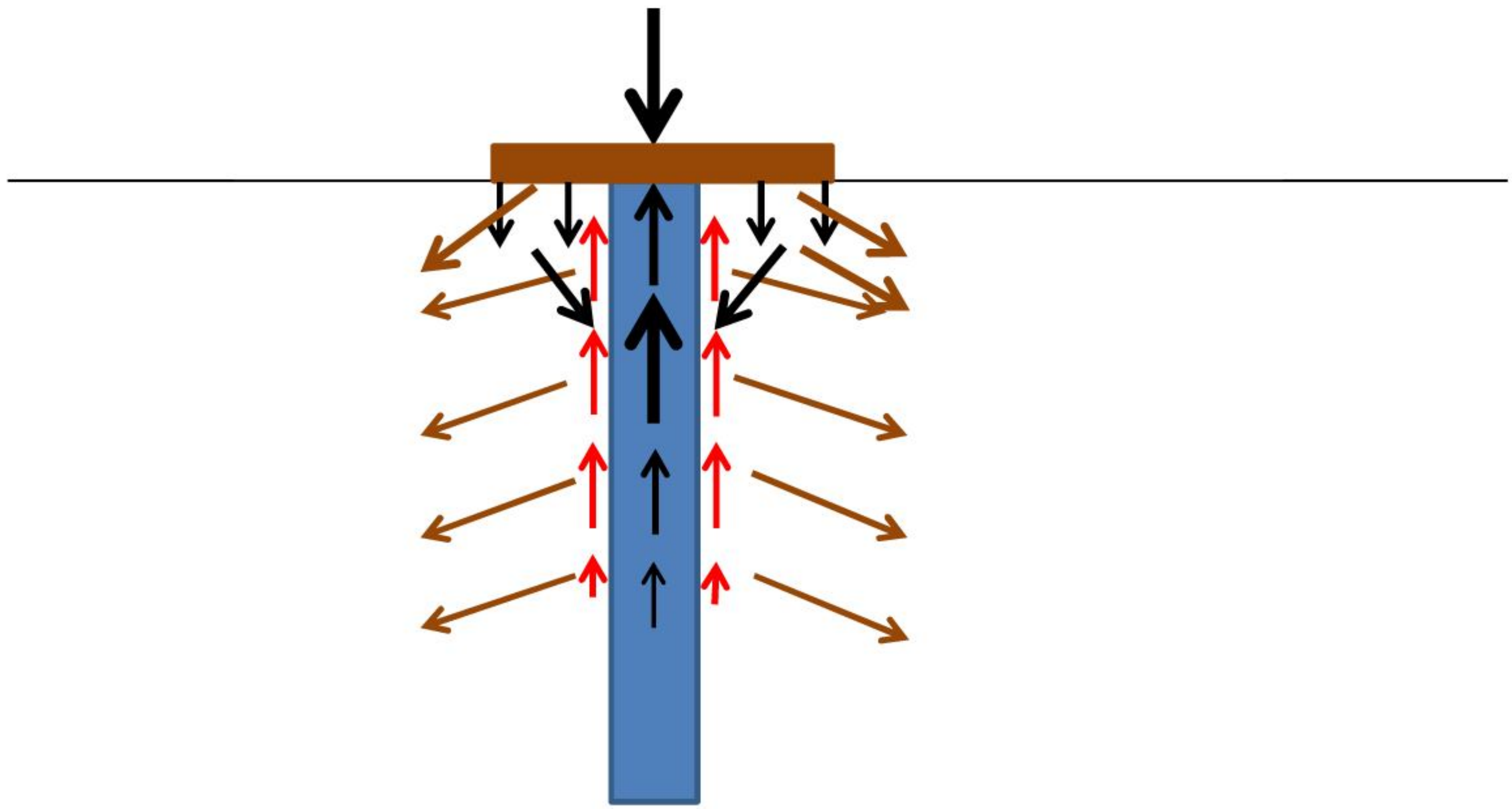
Load Test on Column



Load Test on Column w/ Ftg



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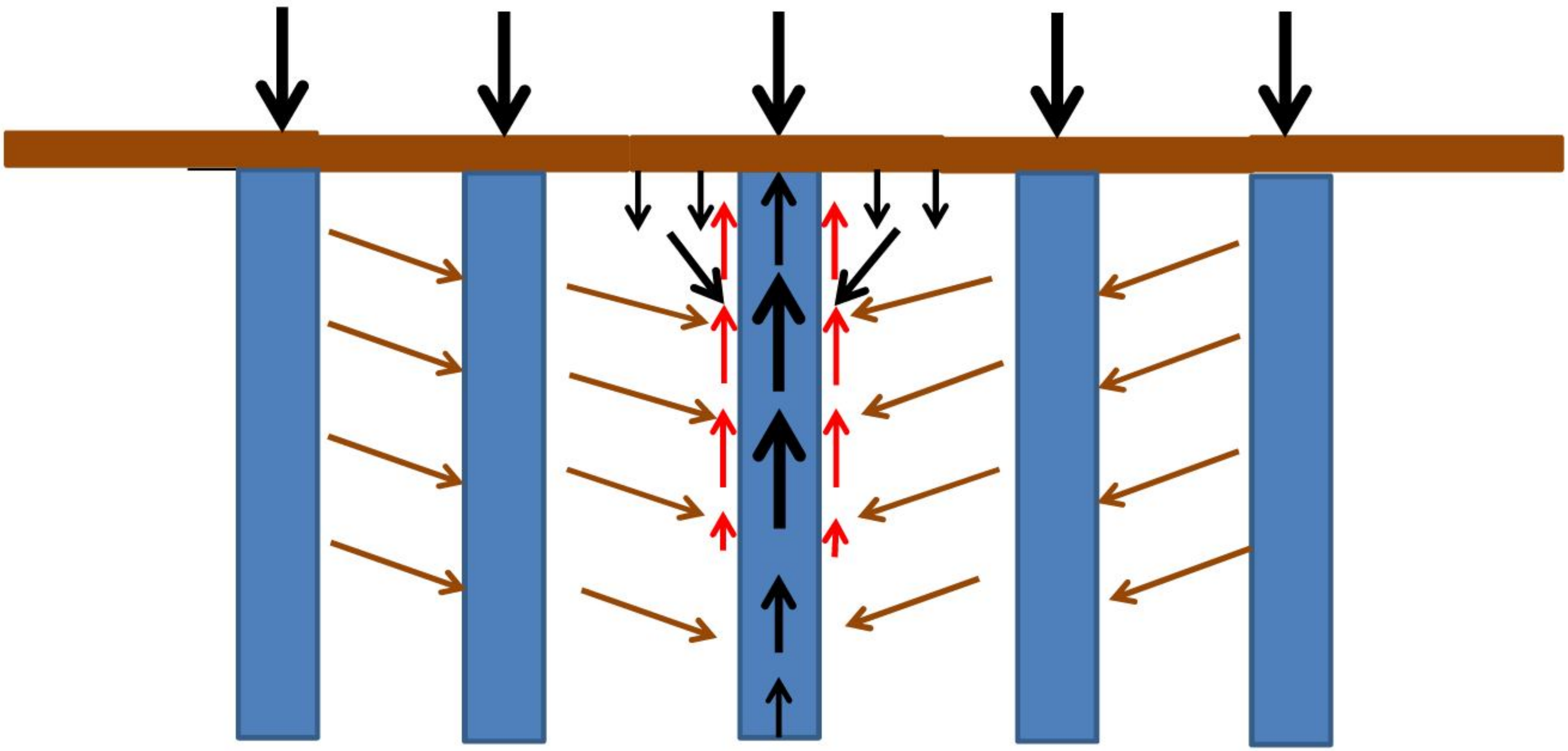
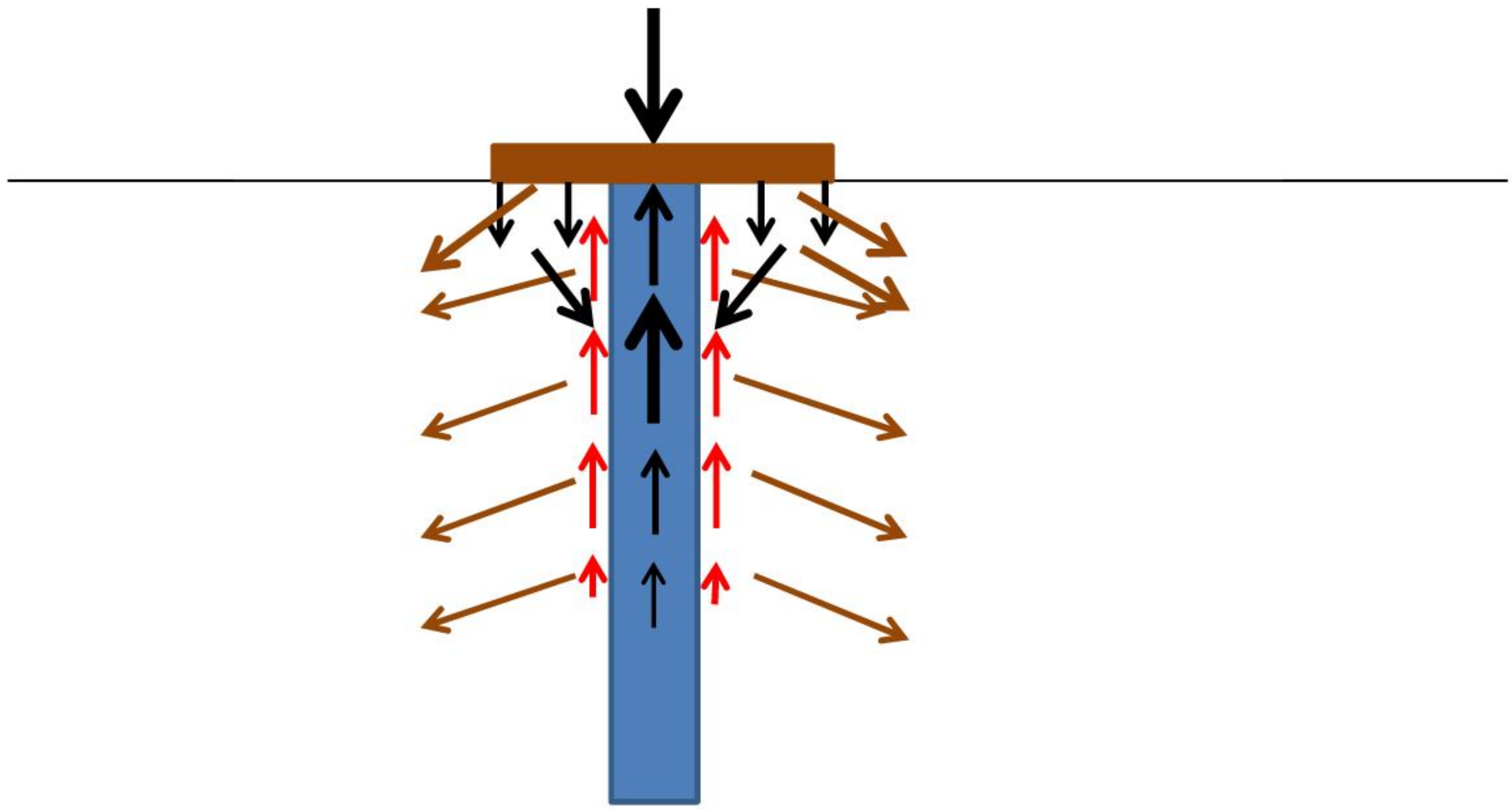
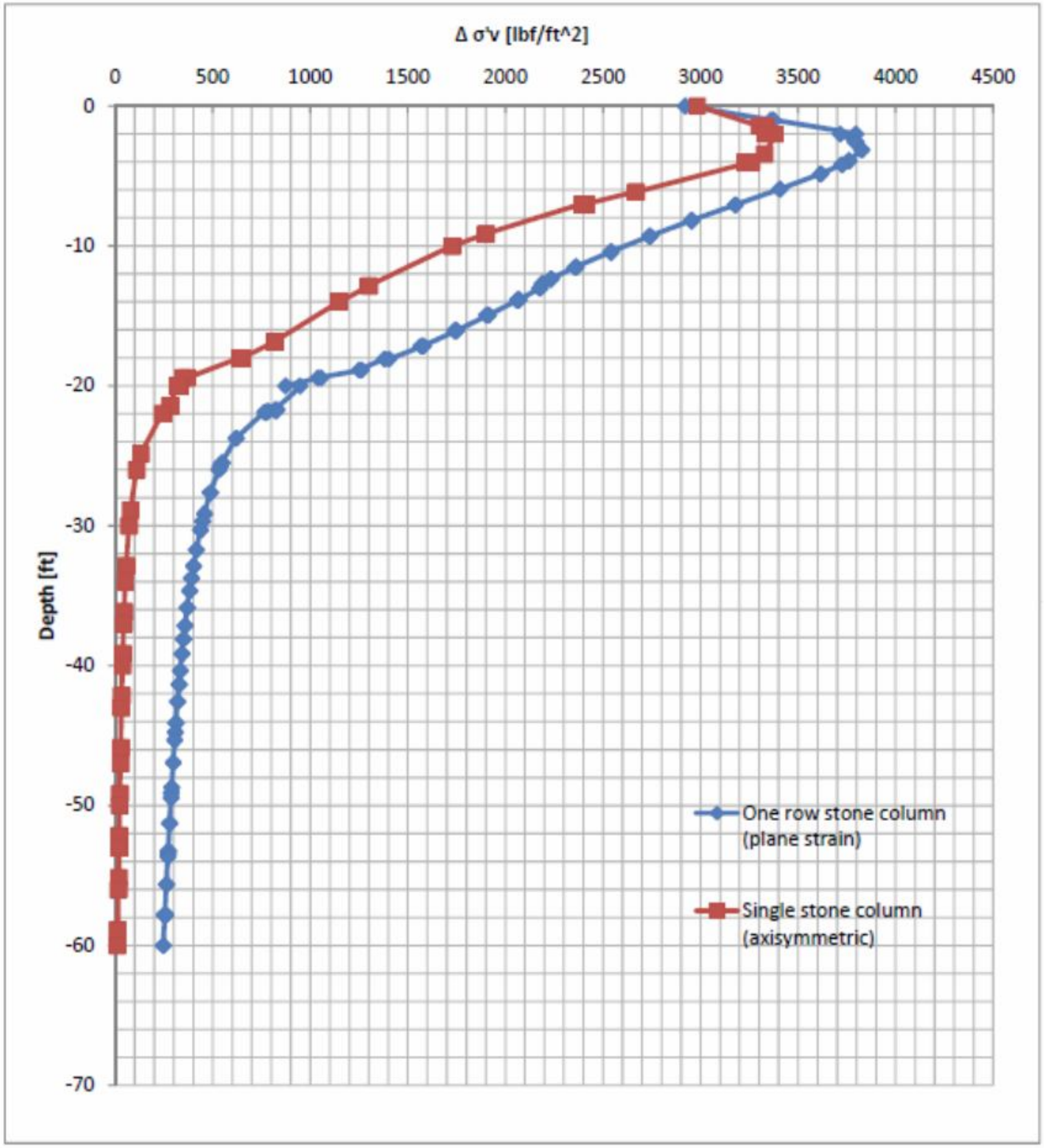
Loaded Row of Columns

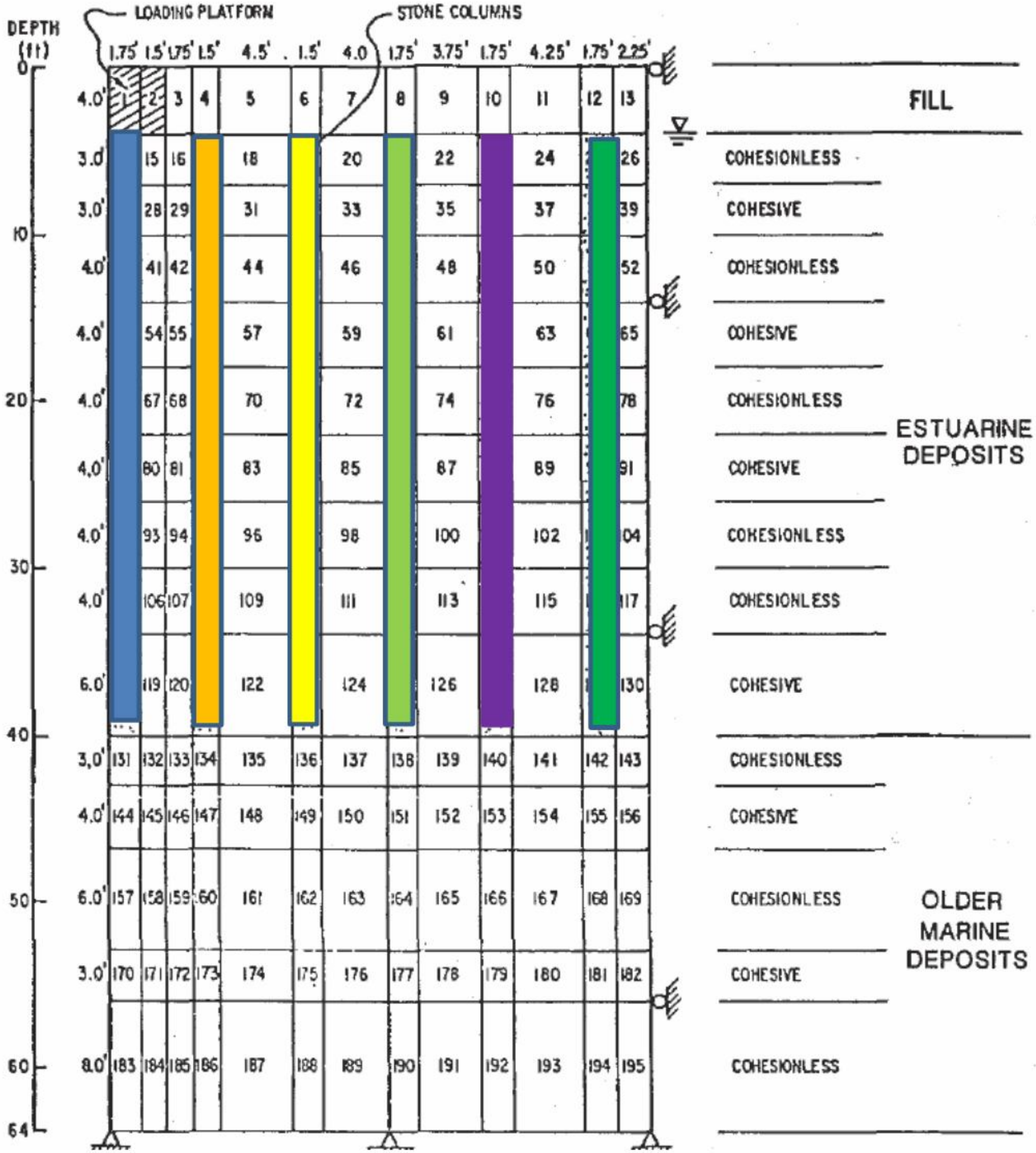


Load Test on Column w/ Ftg

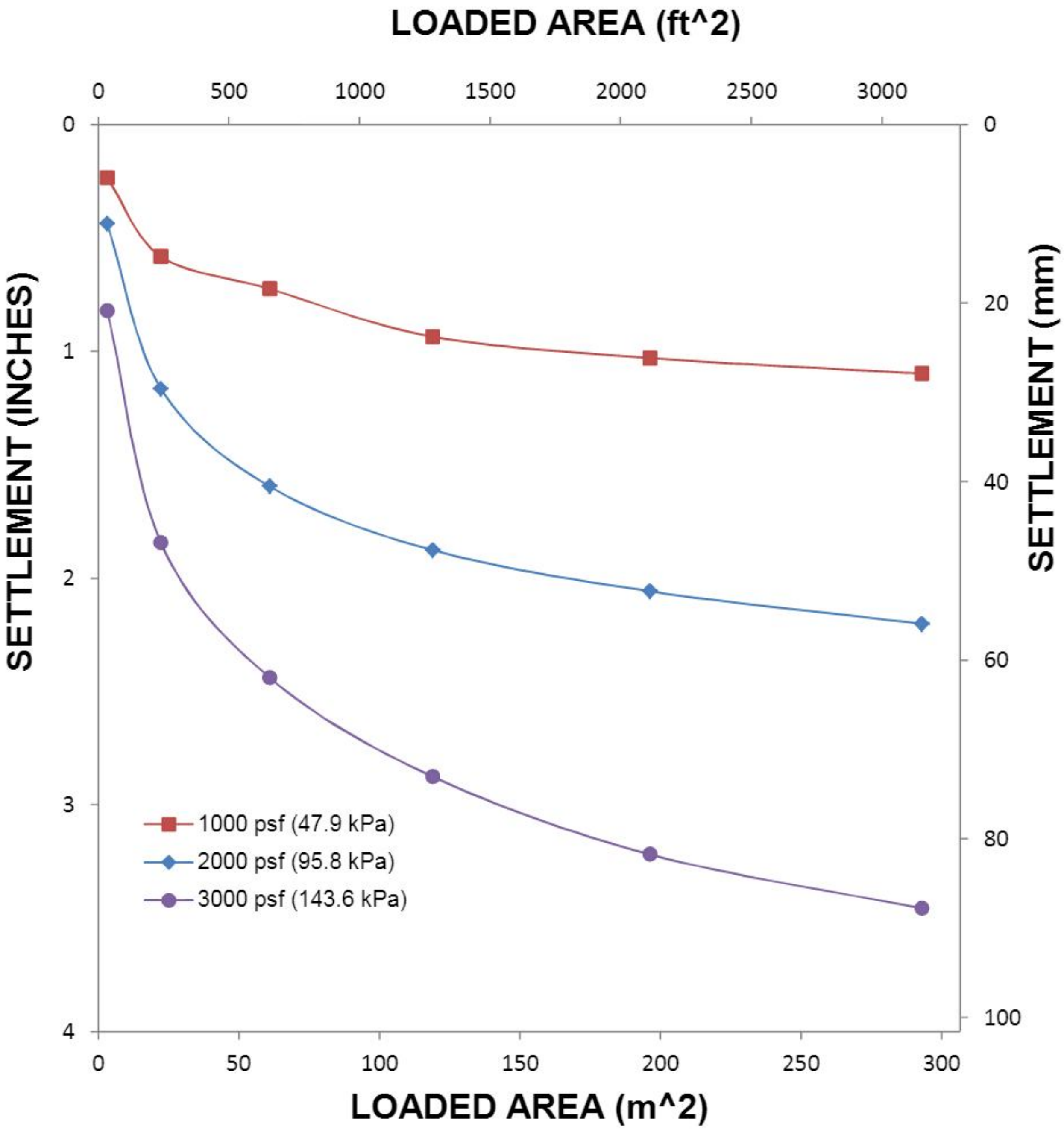


FEM Analyses : Single Col and Single Row of Cols




DEPTH (ft)
LOADING PLATFORM
STONE COLUMNS
1.75' 1.5' 1.75' 1.5' 4.5' 1.5' 4.0 1.75' 3.75' 1.75' 4.25' 1.75' 2.25'
FILL
COHESIONLESS
COHESIVE
COHESIONLESS
COHESIVE
COHESIONLESS
COHESIVE
COHESIONLESS
COHESIONLESS
COHESIVE
ESTUARINE DEPOSITS
COHESIONLESS
COHESIVE
COHESIONLESS
COHESIVE
COHESIONLESS
OLDER MARINE DEPOSITS

Group size effect



Maria Jose Hermandez Gonzalez ,
NCSU Graduate student,
Developed this graph, 2013,
based on Mitchell and Huber paper.

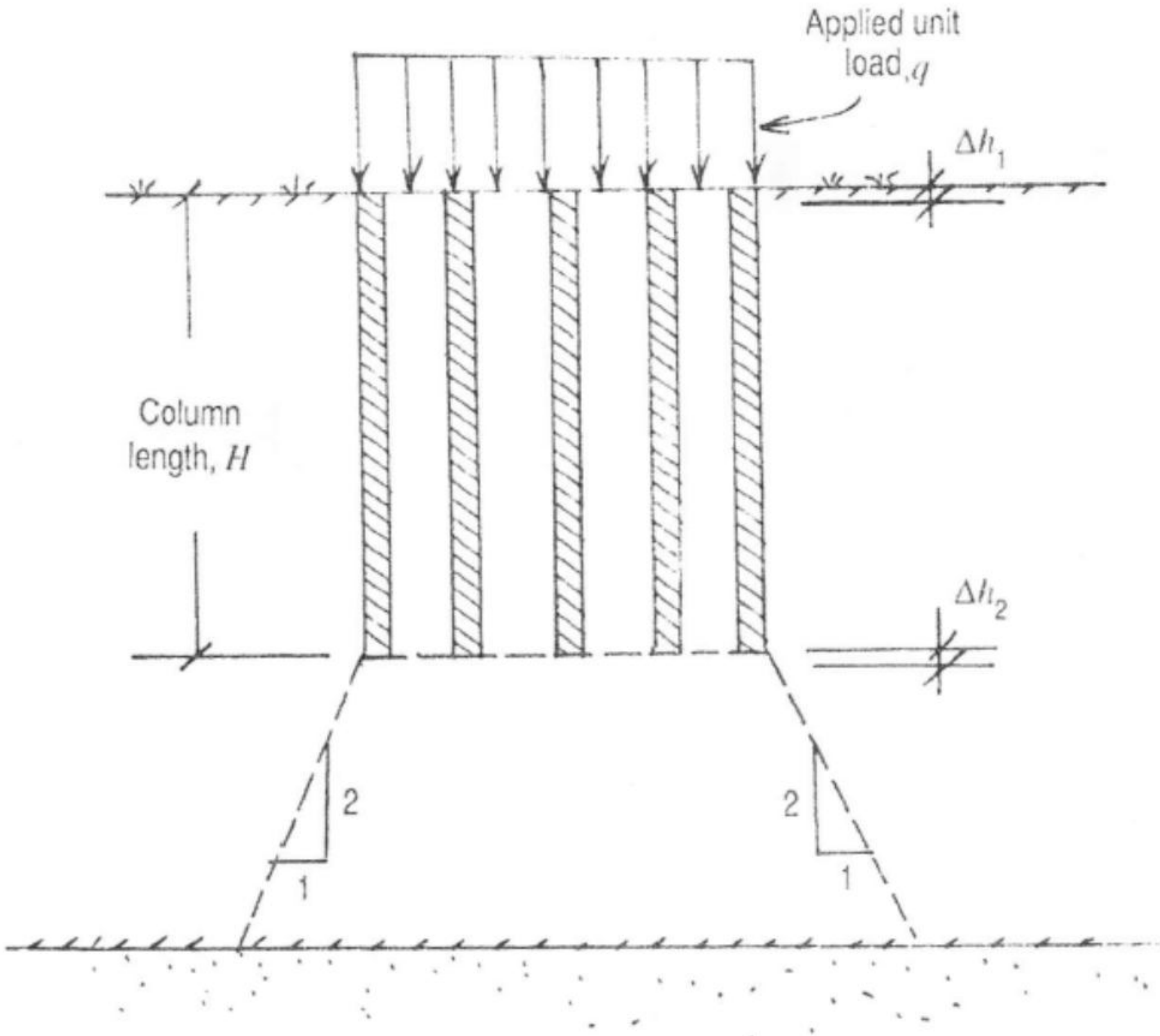
Single Column Tests & Unit Cell

- 1. A single column test is NOT the equivalent of the Unit Cell Model.
- 2. In a load test the load is transferred away from the column into the soil.
- 3. In a very large column group the load in the column is transferred to the bottom of the column (as in the Unit Cell) and the Column Compression is Greater.

Settlement of Footings supported by Aggregate Piers

- Again, the total ground-surface settlement is potentially made up of two parts:
  - 1) compression of the reinforced zone, and
  - **2) compression of the zone beneath the columns**.
- For cases in which non-toe bearing columns, or "floating columns", are used, the calculation of compression in the lower layer is fundamentally based on determining the increase in vertical stress transferred to that layer and the soil modulus.
- In addition to computing elastic settlements, consolidation and/or secondary compression (creep) analyses may also be required.

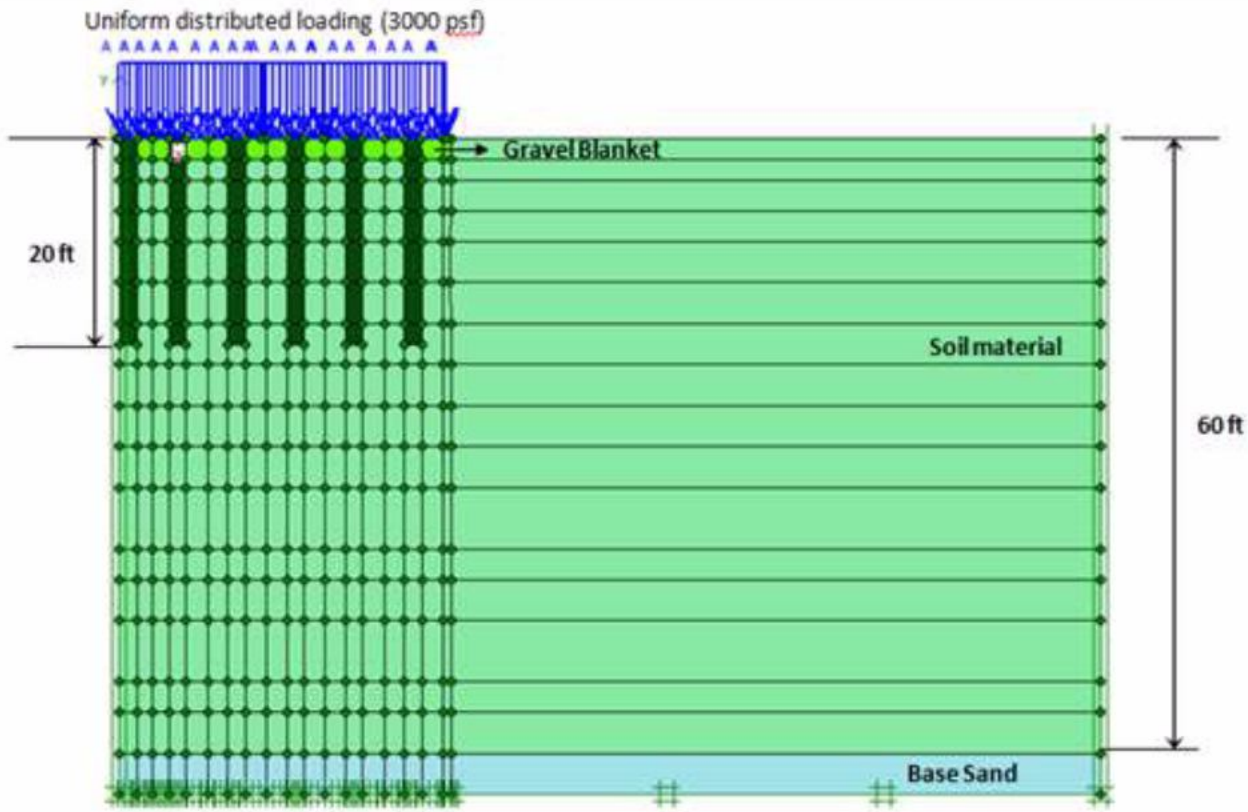
Insight Provided by Broms on Stress Distribution Below Lime Column Groups: (a) When stresses in columns are below creep strength of columns.



FEM Analysis of Single Columns and Column Groups of Increasing Size (number of columns)

- Axisymmetric analysis of single pile and pile group, after approach of Mitchell and Huber (1985).
- Stresses in columns and beneath column group varies with location.
- Significant observations can be made from results of analyses on loaded groups of columns of different areas at the same A_r.

Geometry of FEM model



Material Parameter

Material	Model	$\gamma(lb/ft^3)$	$E(ksf)$	ν	$c(psf)$	ϕ(deg.)
Gravel Blanket	Plastic	127	236	0.23	-	45
Soil	Plastic	110	**100**	0.33	100	30
Stone column	Plastic	127	**355**	0.23	-	45
Base sand	Plastic	120	500	0.3	-	35

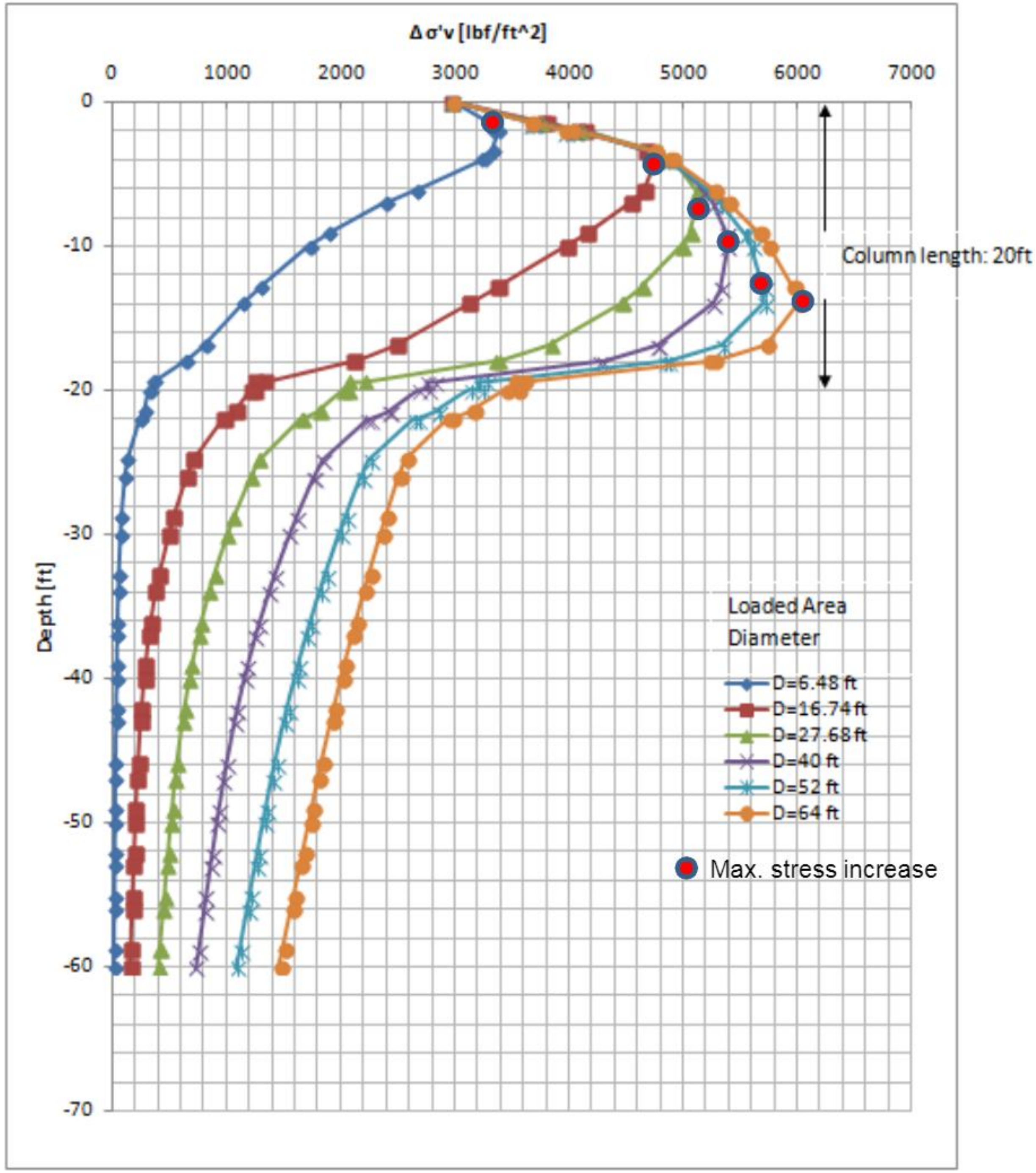
Uniform Surface Loading of 3000 psf

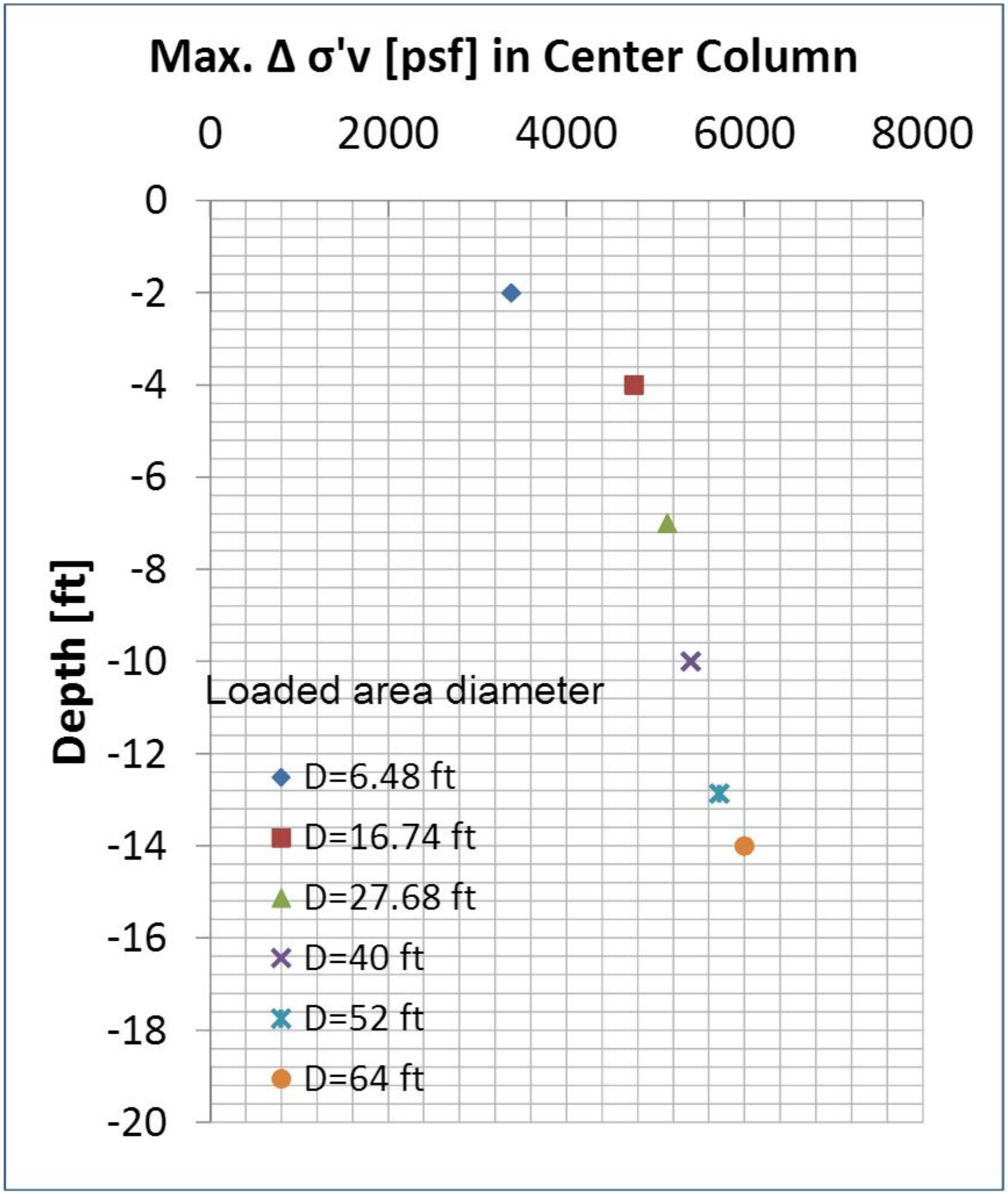
Drained Material Properties:

Soil: E = 100 ksf
ν = 0.33
Φ soil = 30^0

Columns: E = 355 ksf
ν = 0.23
Φ stone = 45^0

Ar = 0.29



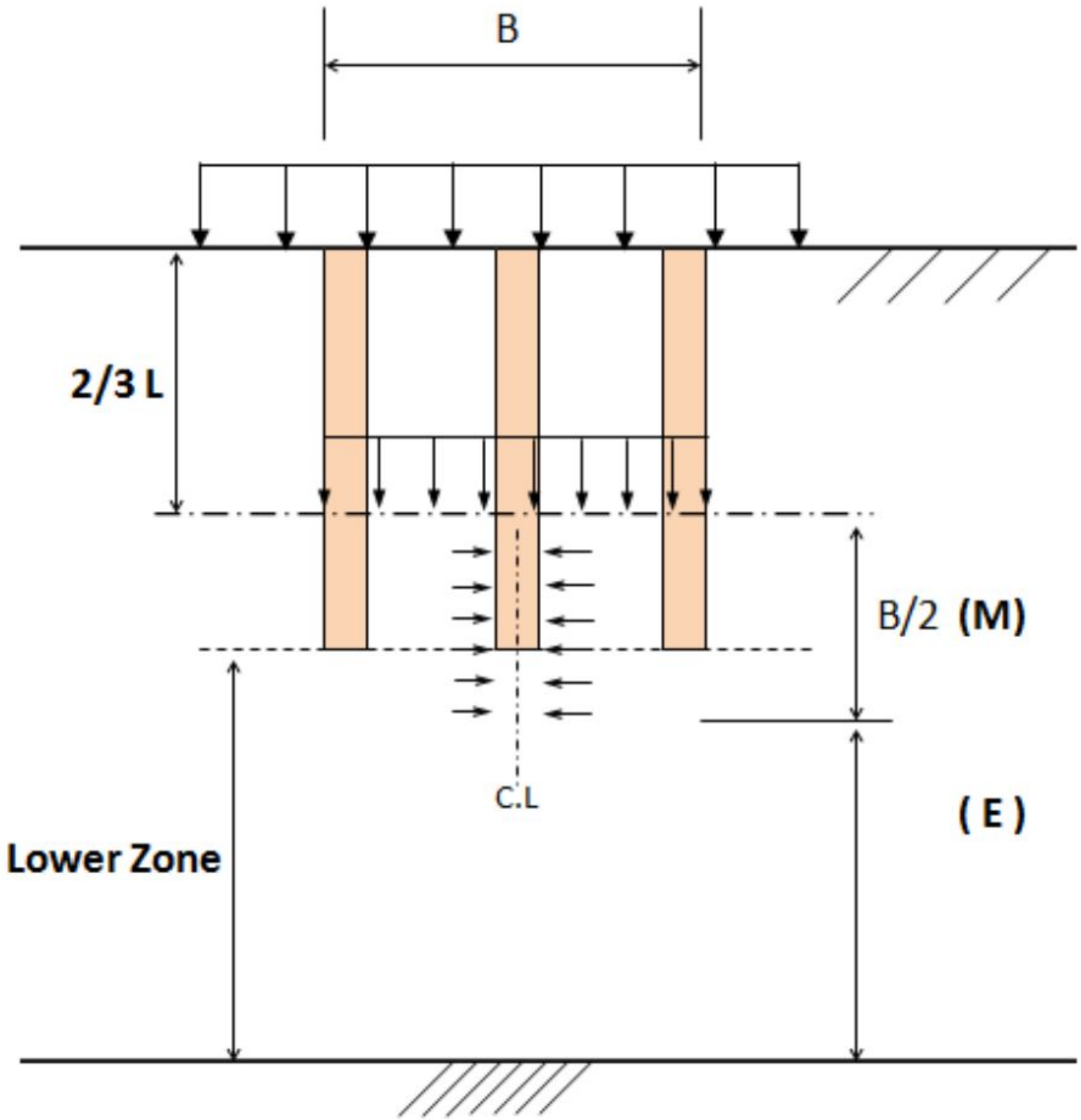


Max. Δ σ'v [psf] in Center Column
0
2000
4000
6000
8000
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
Depth [ft]
Loaded area diameter
D=6.48 ft
D=16.74 ft
D=27.68 ft
D=40 ft
D=52 ft
D=64 ft

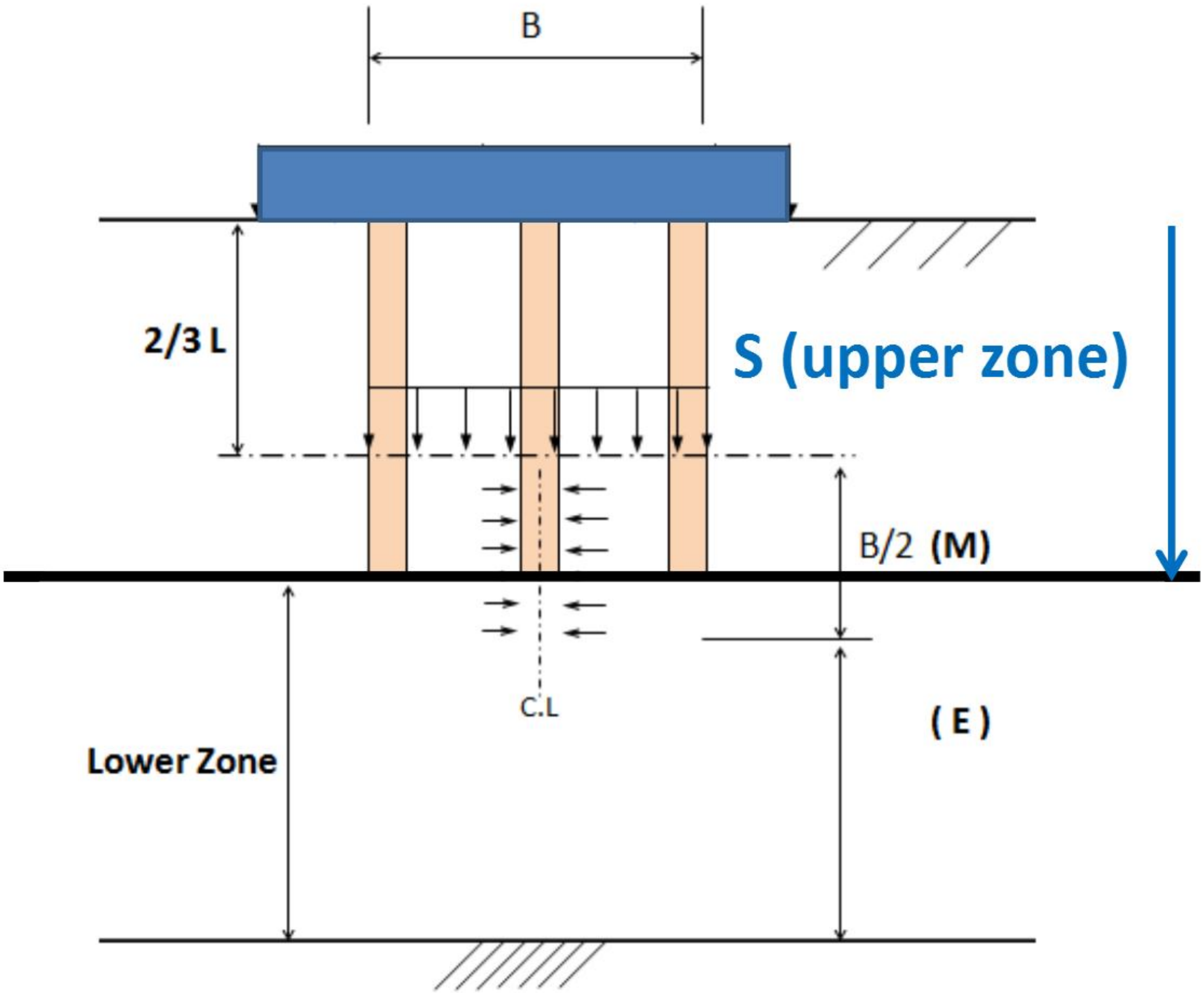
Analysis of Stress Distribution beneath Aggregate Pier Column Groups

- Based on the previous models, the distribution of stress below groups of 20 ft-long columns (with A_r = 0.3) for two different sized areas and the following:
- 1. Boussinesq's solution with loading at 2/3 L.
- 2. FEM Analysis with equivalent circularly-loaded area (for axisymmetric analysis).

Model For “Floating Column” Group

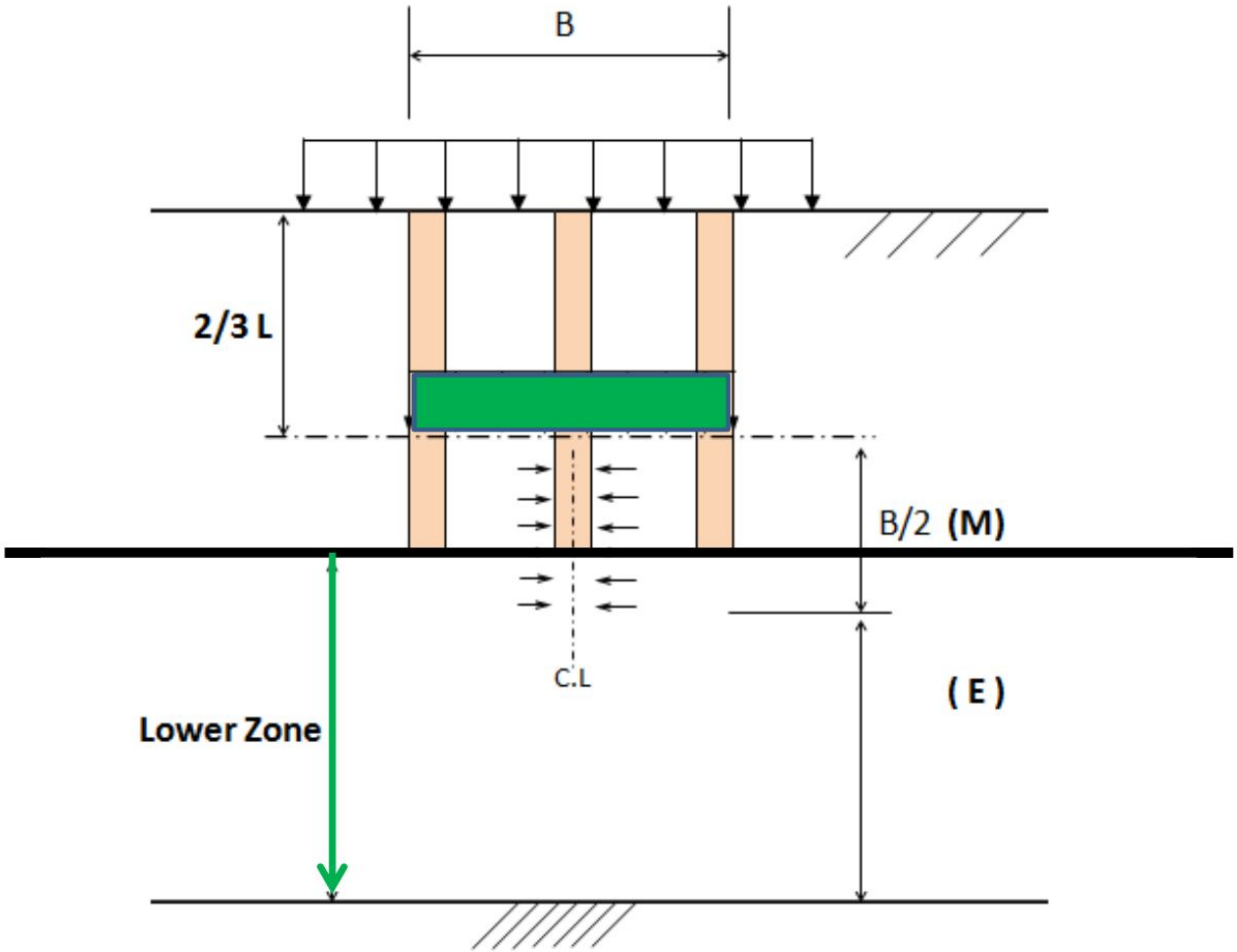


Settlement of Upper Zone
Boussinesq's solution



- Apply loads to profile as if there were no columns and calculate settlement.
- Determine appropriate Performance Ratio (PR) or Settlement Ratio (n) and calculate reduced settlement of Upper Zone
- **S1 = S (upper zone) x PR or**
- **S1 = S (upper zone) / n**

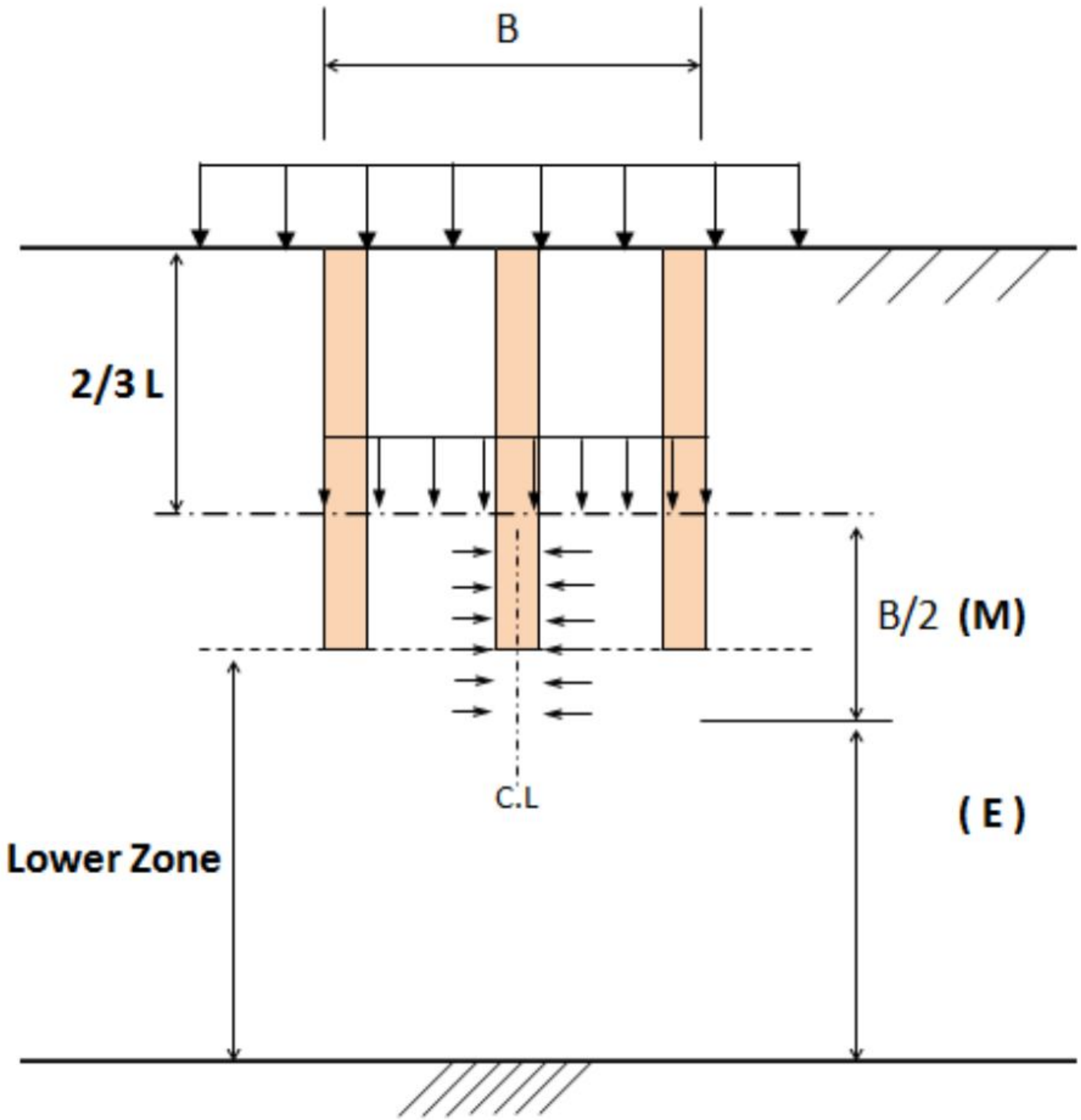
Calculate Settlement in Lower Zone
Boussinesq's solution with loading at 2/3 L



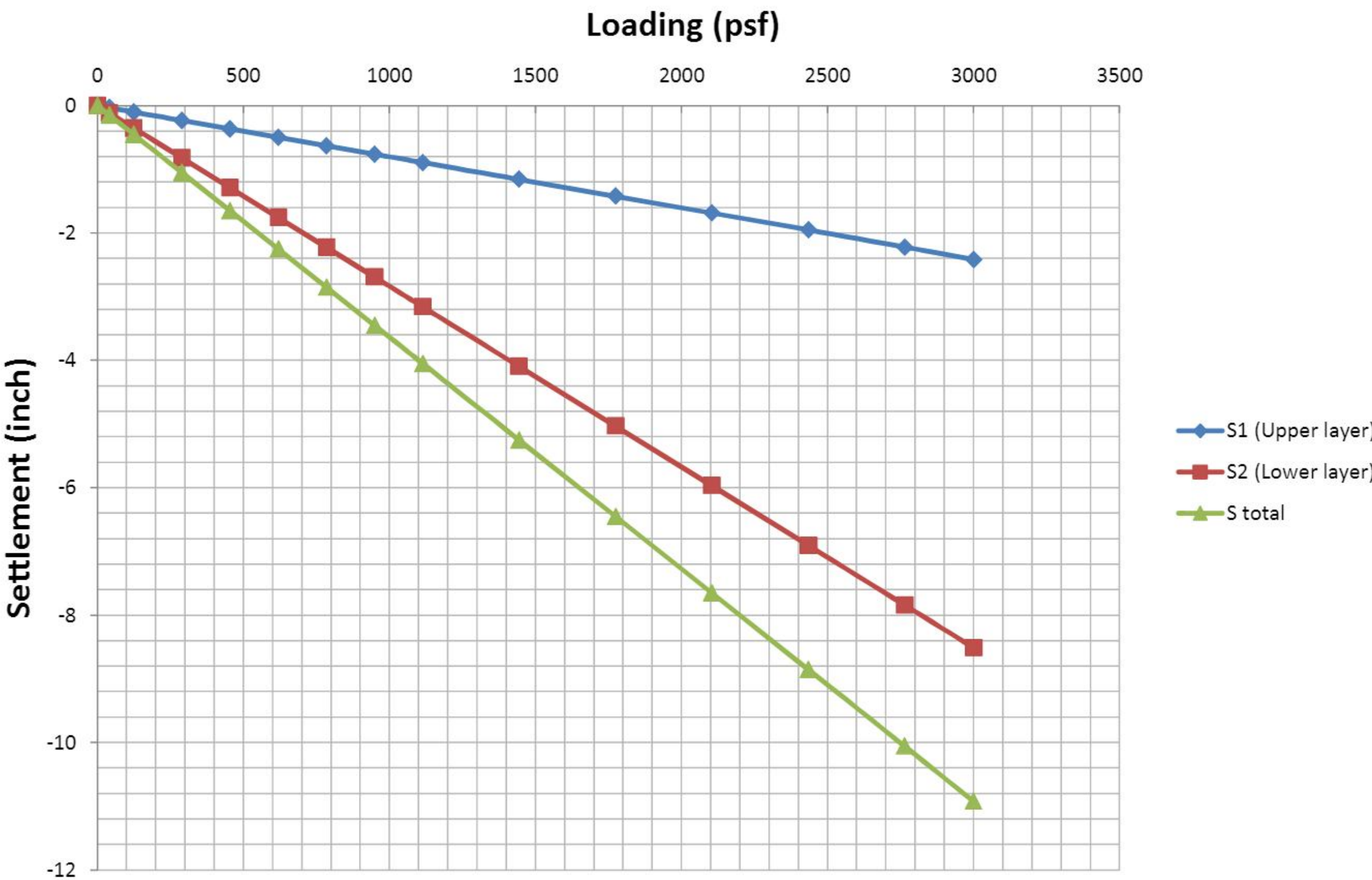
- Apply loads to profile as “imaginary footings” at 2/3 L and calculate settlement in Lower Zone.
- Use Constrained Modulus to depth of B/2 below loaded area (increase in lateral stress – similar to Schmertmann strain-influence diagram).

- **S2 =   S (lower zone)**
- **S = S1 + S2**

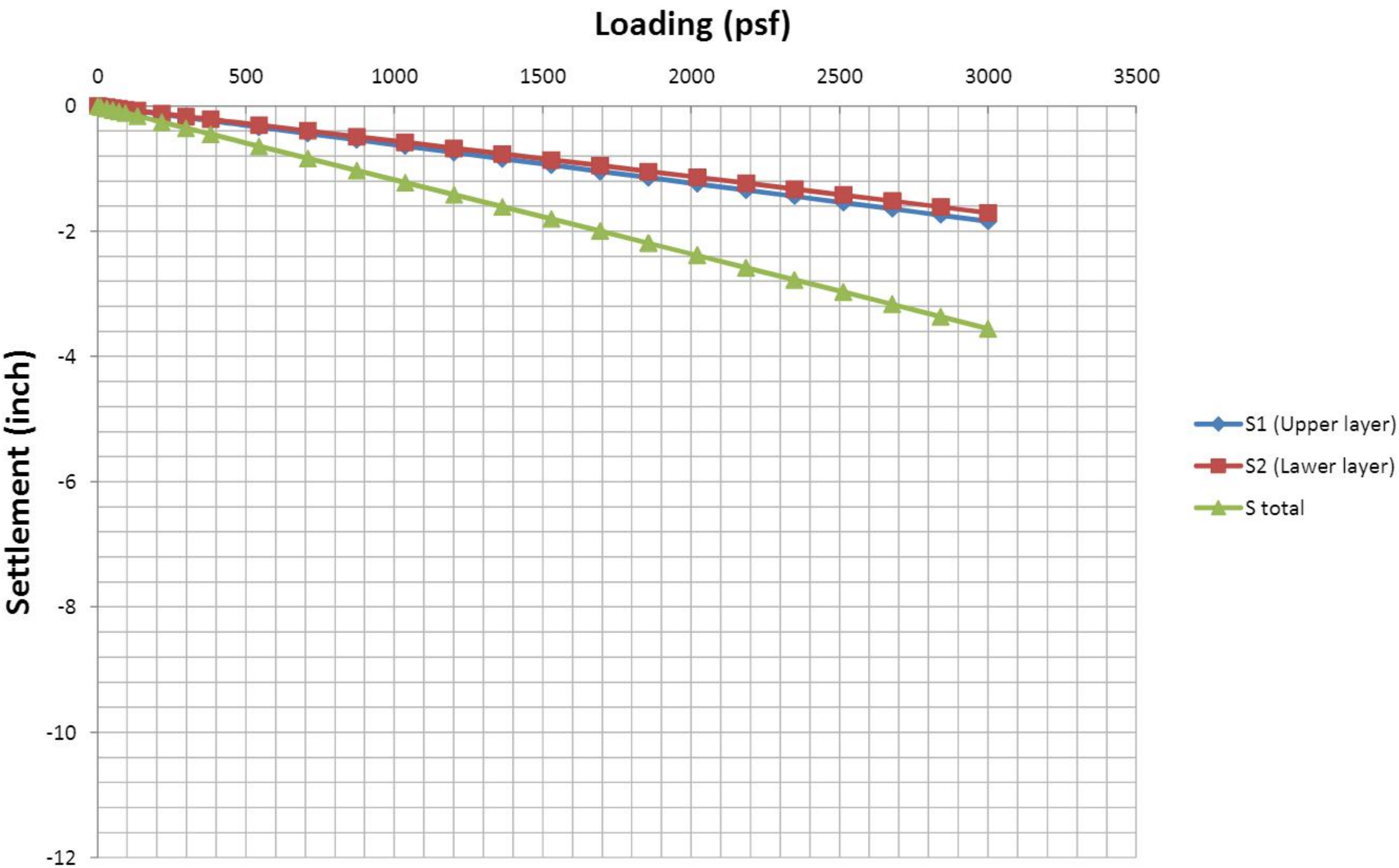
Boussinesq's solution with loading at 2/3 L



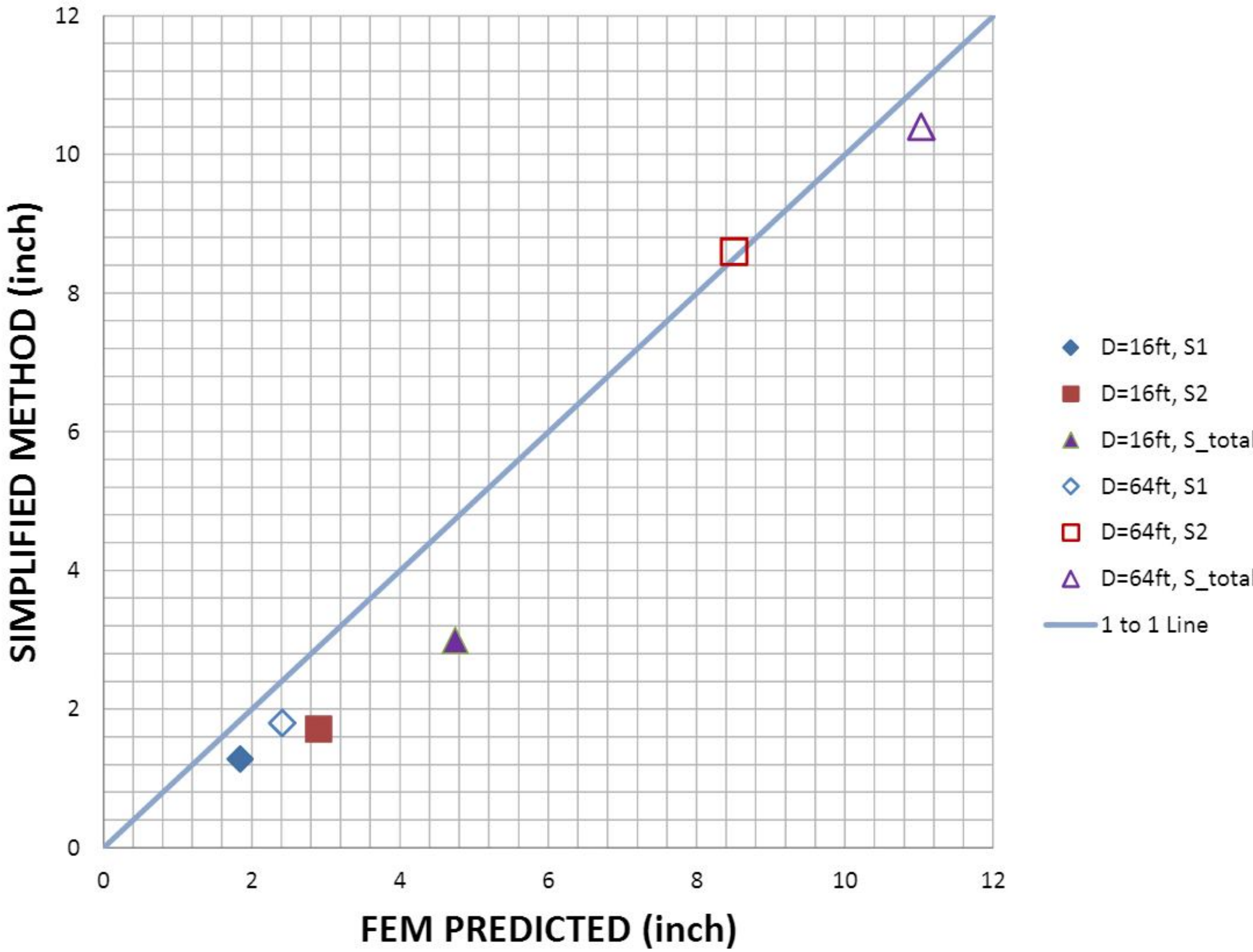
Observations from Stress Distribution Study
FEM Settlement for D = 64ft



Observations from Stress Distribution Study
FEM Settlement for D = 16.74ft

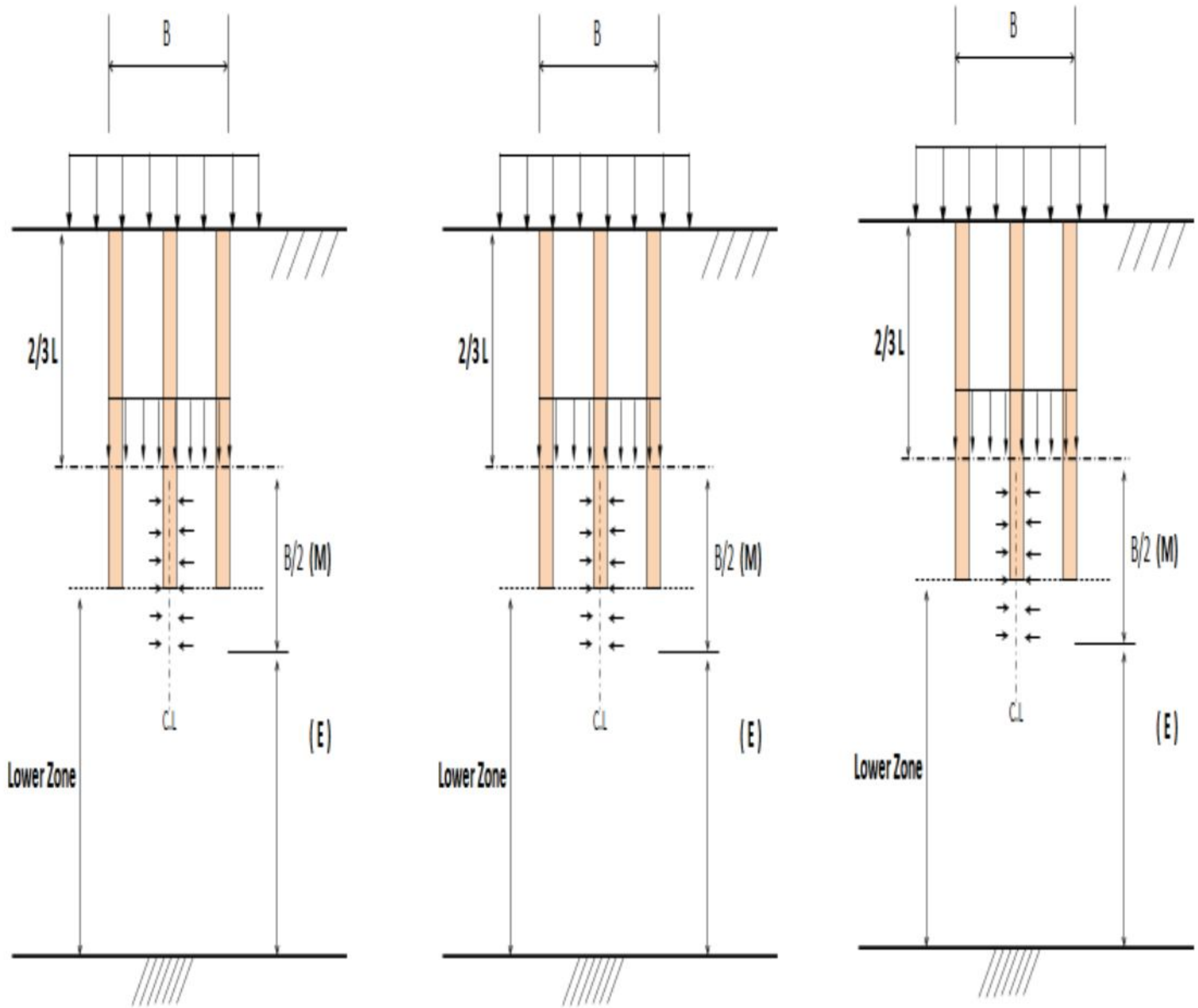


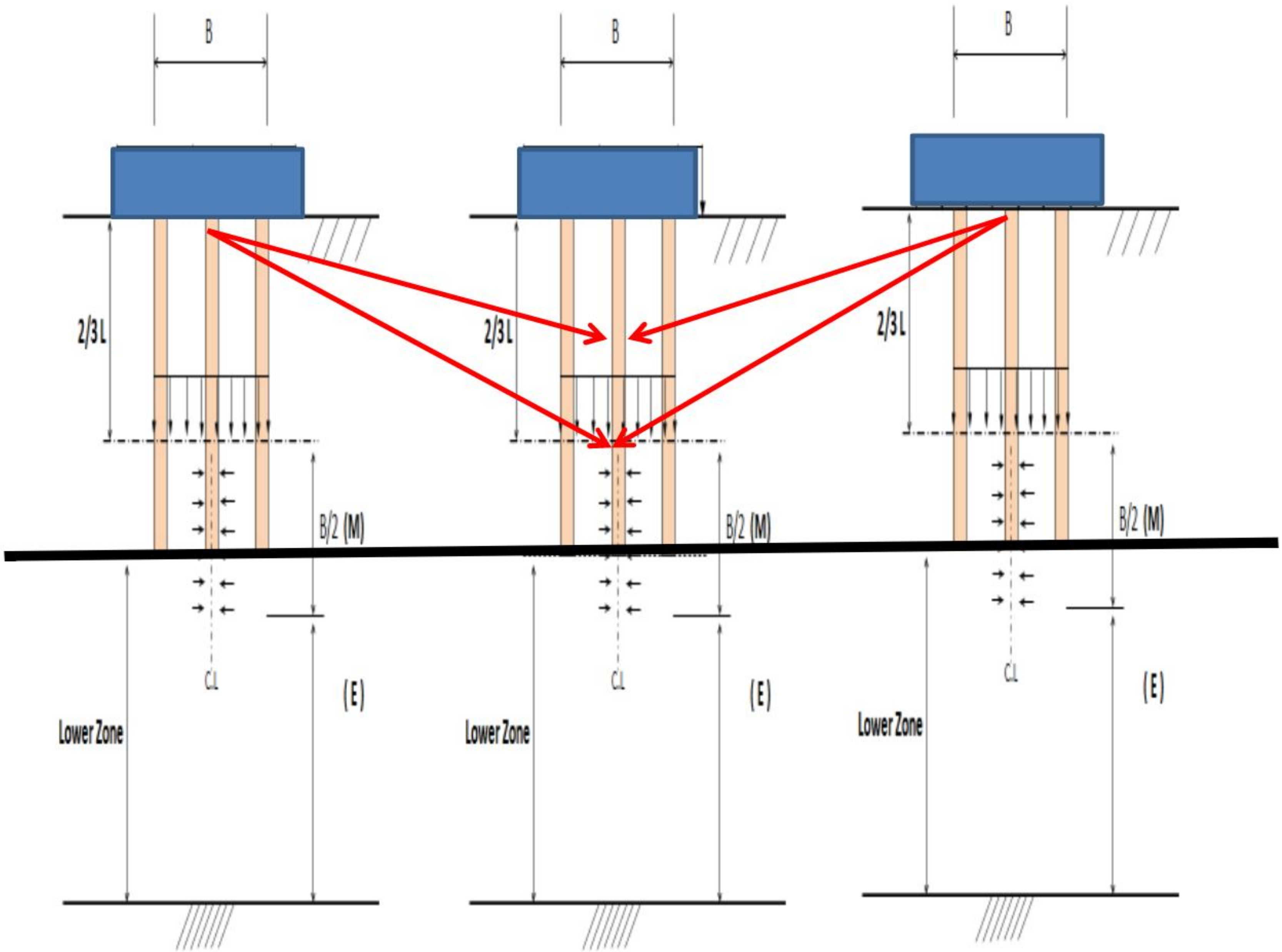
Comparing between simplified method and FEM

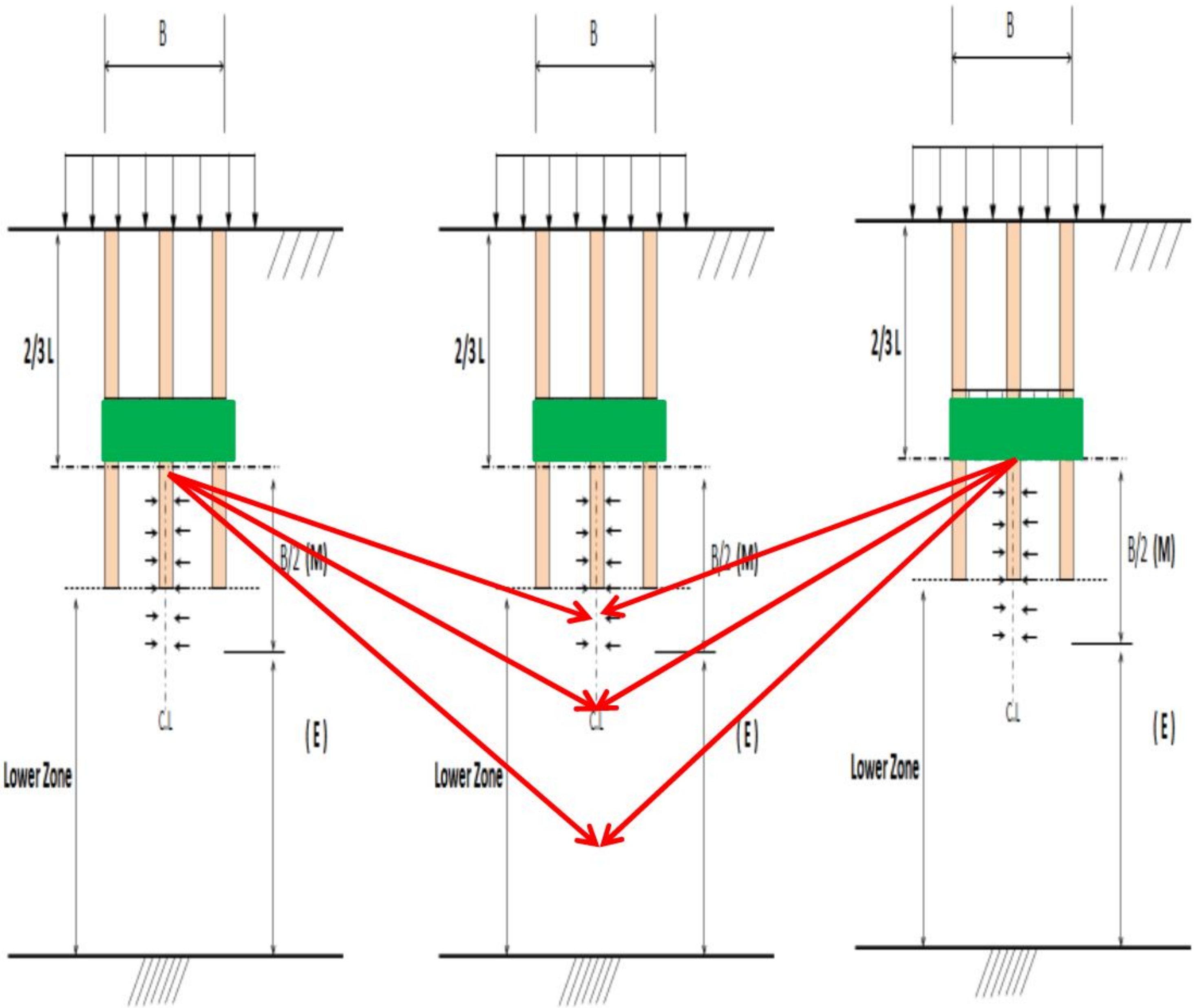


Approach for Multiple Column-Supported Ftgs

- 1. FEM analysis of actual geometry
- 2. “Addition and Subtraction” of Influence Values
- 3. Approximation based on Interaction analysis using loaded areas in Upper Zone and Lower Zone.


B
2/3L
B/2 (M)
C.L
(E)
Lower Zone
B
2/3L
B/2 (M)
C.L
(E)
Lower Zone
B
2/3L
B/2 (M)
C.L
(E)
Lower Zone


B
B
B
2/3L
2/3L
2/3L
B/2 (M)
B/2 (M)
B/2 (M)
CL
CL
CL
(E)
(E)
(E)
Lower Zone
Lower Zone
Lower Zone


B
B
B
2/3L
2/3L
2/3L
B/2 (M)
B/2 (M)
B/2 (M)
C.L
C.L
C.L
(E)
(E)
(E)
Lower Zone
Lower Zone
Lower Zone

Conclusions

1. Upper Zone (reinforced zone) compression is a function of:

   -**Area Replacement Ratio, Ar,**

   -Column Length, and

   -Area Improved and Loaded (number of columns),

   as well as column properties and surrounding soil properties).

2. Lower Zone compression can be approximated using an "imaginary footing" at 2/3L to calculate stresses using Boussinesq theory (unconservative for small groups).

3. To approximate the influence of increased lateral stresses in the zone directly beneath the loaded area, it is proposed to use M to a depth of B/2 below the "imaginary footing depth" and then E below.

Conclusions (cont.)

4. The settlement observed during a Load Test on a single column will not be the settlement of a footing or mat when multiple columns are involved (at commonly used Ar values), unless the columns are short and end bearing.
5. The magnitude and significance of the interaction effect between columns increases as the number of columns increases.