A Simplified Design Methodology for Estimating the Settlement of Footings and Mats Supported by Stone Columns and Aggregate Piers

Jungmok Lee and
Roy H. Borden

Department of Civil, Construction and Environmental Engineering
NC State University

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**)

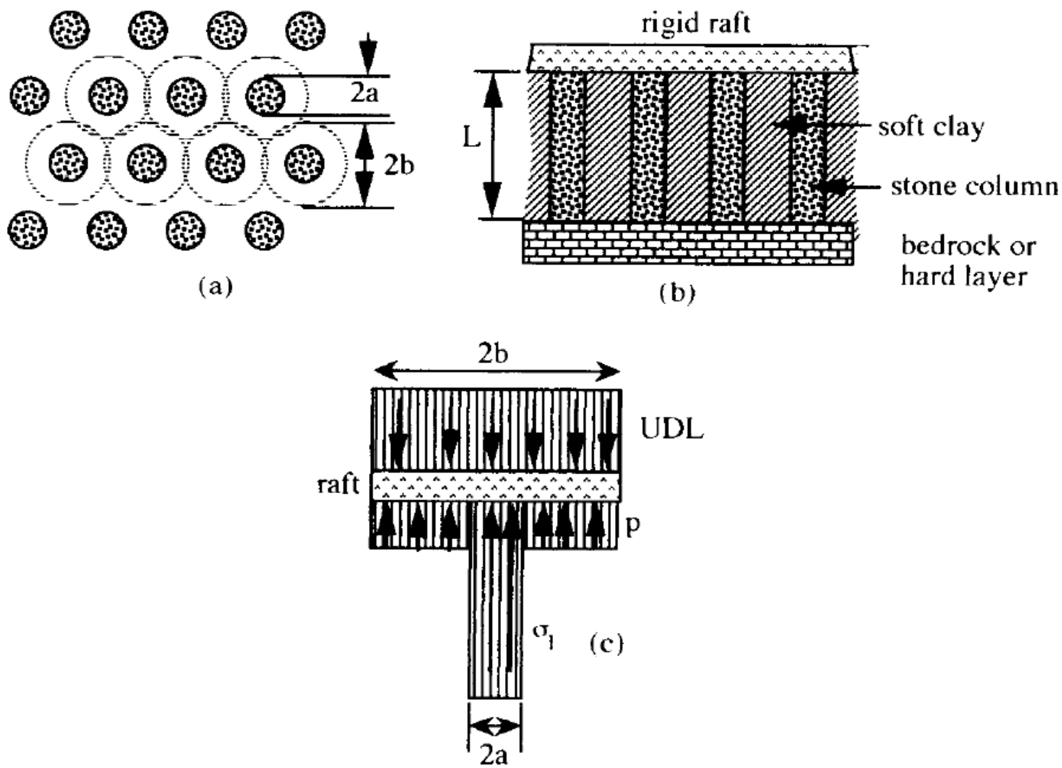


Fig. 1. Key figure, $2a$ = column diameter, $2b$ = spacing.

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

- Vibro-replacement stone columns to support a large wastewater treatment plant founded on up to 48 ft of soft estuarine deposits.
- Foundation stresses were up to 3000 psf.
- The basic design was a loading of 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 analyses 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%.**

Mitchell and Huber, 1985 (cont.)

- 28 **single-column loads tests** were performed during installation of the 6,500 stone columns.
- **The installation of stone columns led to a reduction in settlements to about 30-40% of the values to be expected on 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

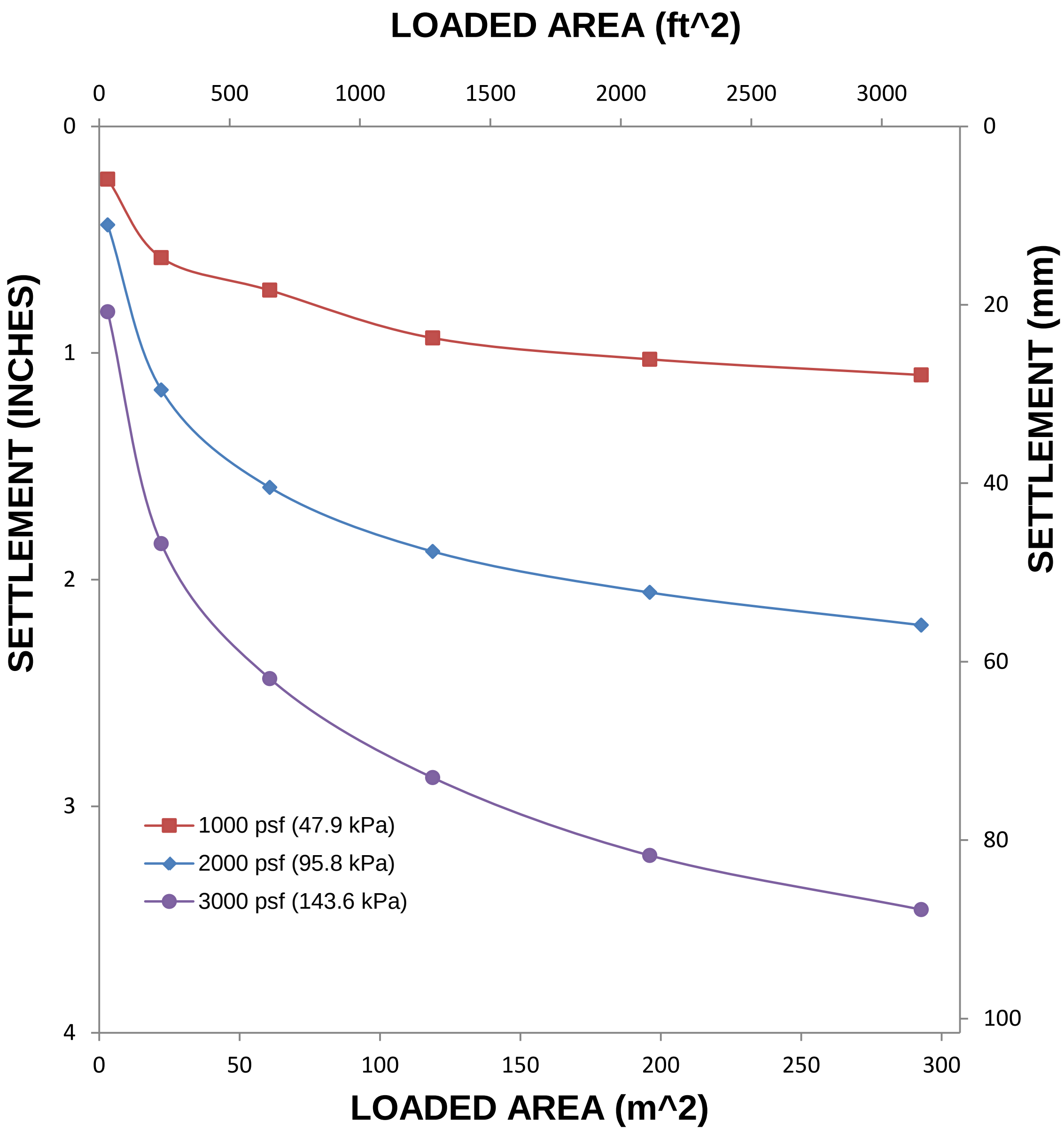
Mitchell and Huber, 1985 (cont.)

- **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.

Group size effect



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

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.

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:

- $n = \dfrac{\left(\frac{ULD}{E_S}\right)}{\left(\frac{\delta}{L}\right)} = 1 + A_r \left(\frac{E_C}{E_S} - 1\right)$
- 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 = 0.32

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

Poorooshasb and Meyerhof, 1997 (cont)

- “The **performance ratio** is defined as the ratio of the settlement of the treated ground (ground with stone column inclusions) to that of the untreated ground under identical surcharges.
- *“performance ratio = (settlement ratio)$^{-1}$ or* ***PR = 1 / n***
- ***“For a well compacted stone fill (*** *ϕ = 44^o* ***) the performance ratio is 0.31.”***
- ***“Thus if the settlement of a foundation system without stone columns is, say, 20 cm*** [8 in], ***inclusion of the columns would reduce its settlement to 0.31 x 20, or about 6 cm*** [2.5 in].”
- [ed: assuming the loaded area is large- many columns]

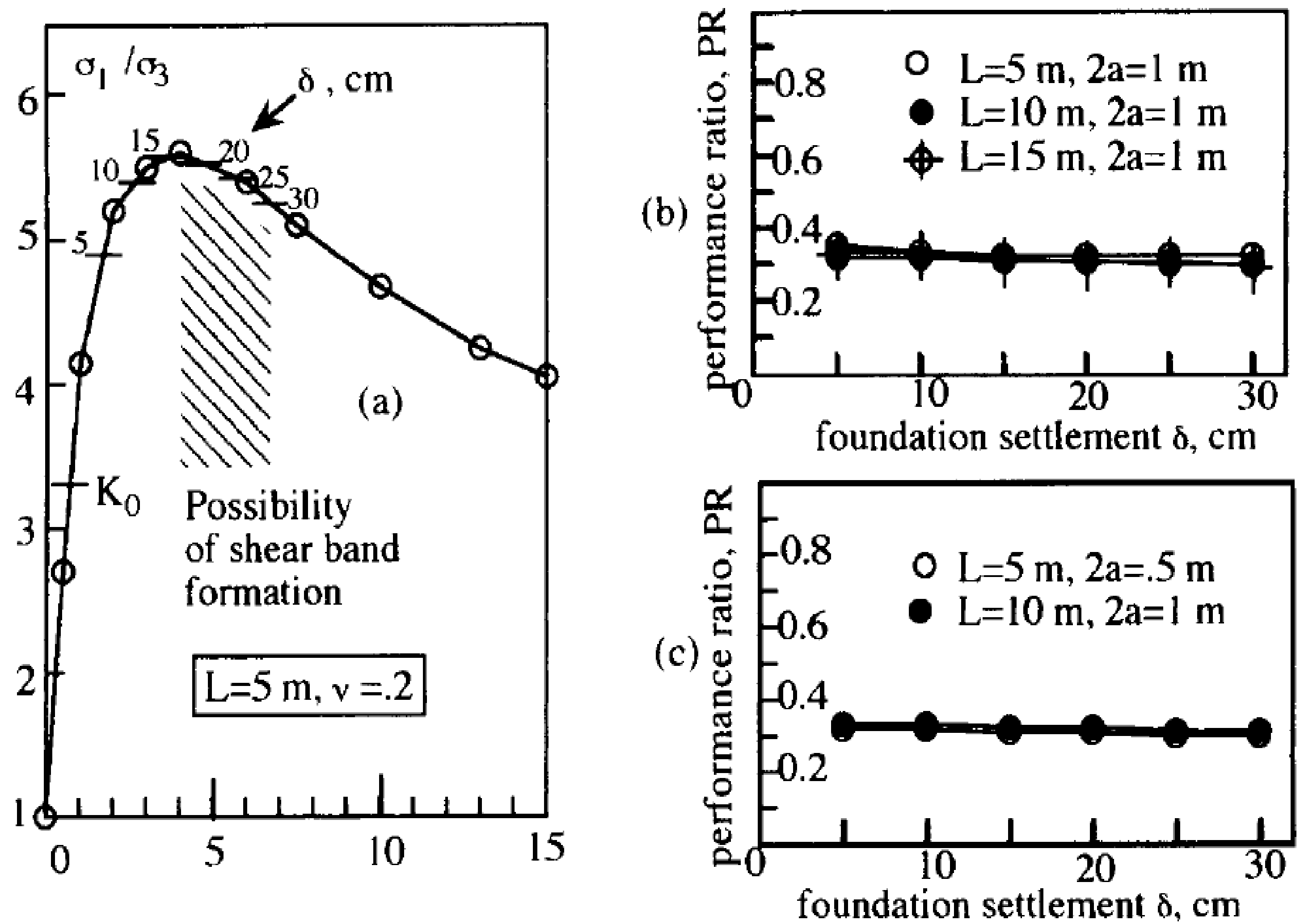


Fig. 4. Effect of column length on the performance ratio.

Poorooshasb and Meyerhof, 1997 (cont)

DESIGN CHARTS

The design charts produced here are based on derived in the last section. For a proposed s, ϕ and ε_f they provide the value of PR which is, in turn, given by the equation;

$$PR = \frac{\delta}{H}\frac{E'}{UDL} \tag{12}$$

In Eqn 12 δ is the settlement of the foundation system, H is the height of the soft soil layer, UDL is the magnitude of the uniformly distributed load supported by the mat *plus* the self weight of the mat per unit area and E' is the modified Young's modulus for the soft soil corrected for the Poisson's ratio effect.

Three charts (see Fig. 6) are produced here assuming a value of $v = 0$ as this provides the most conservative estimate of PR. The case where $s = 1$ represents a situation where the soft soil is completely dug out and replaced by stones! Spacings larger than 4 diameters are not considered efficient.

Poorooshasb and Meyerhof, 1997 (cont)

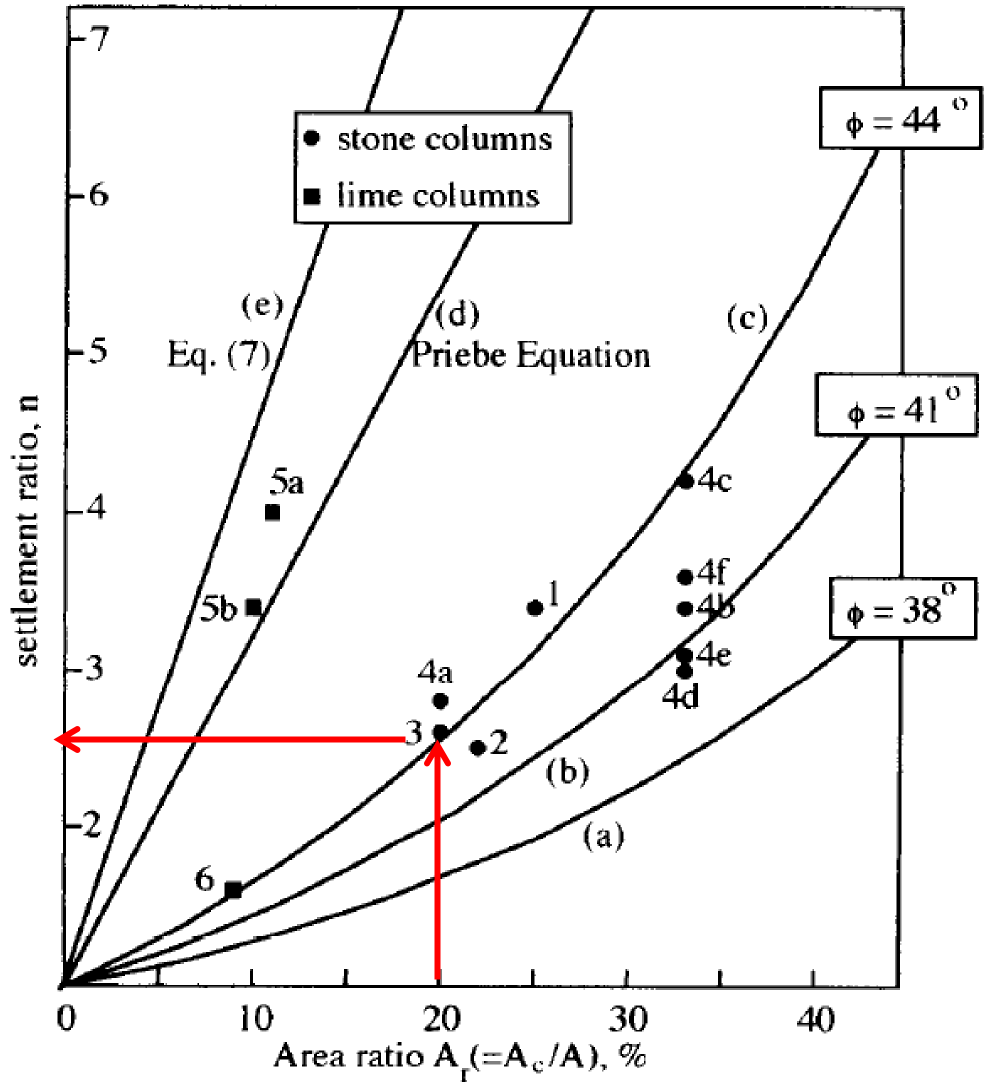


Fig. 7. Settlement ratio vs area ratio for stone columns and lime columns. Comparison of analytical results with field data.

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.

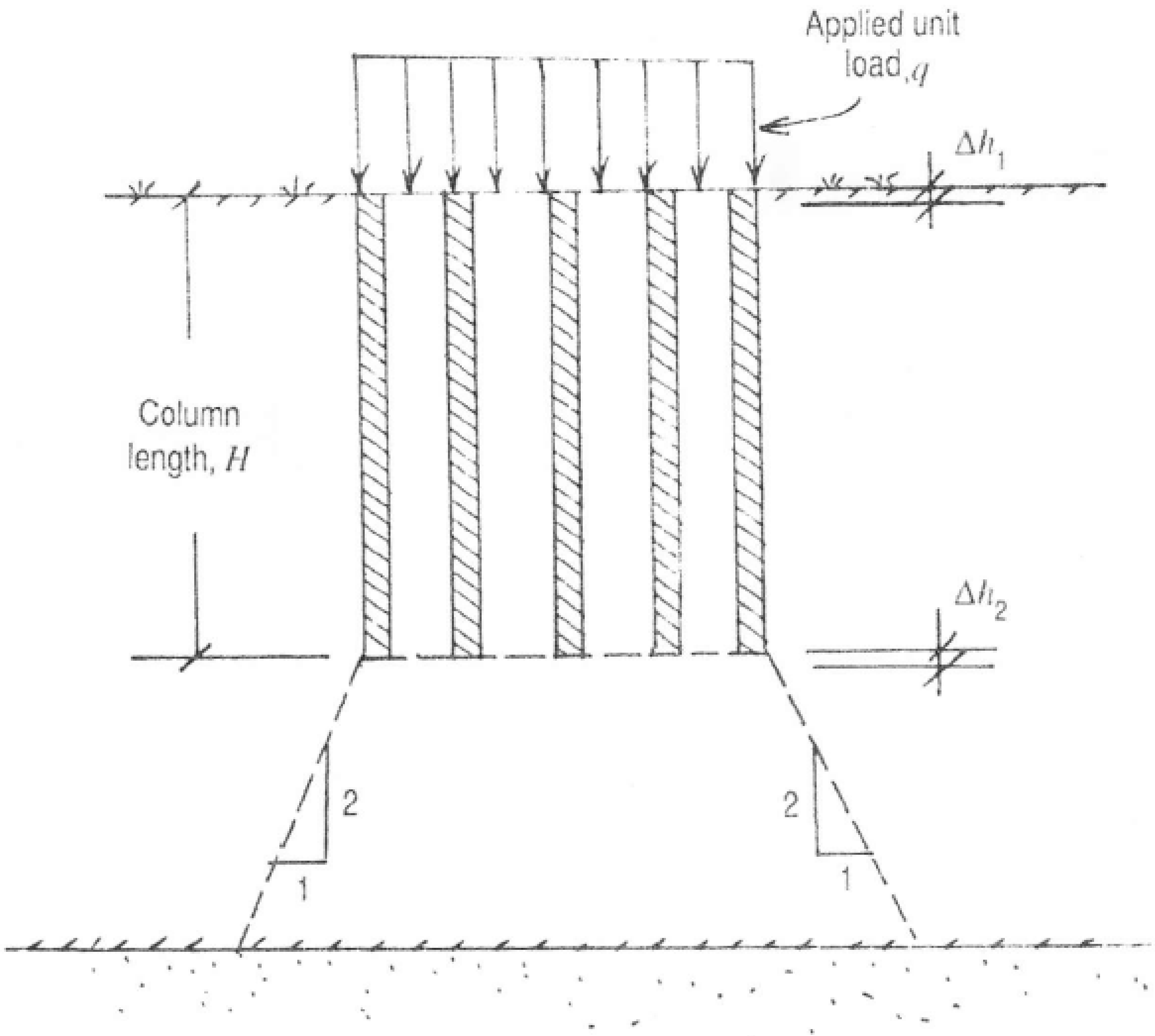
Compression of Zone Beneath Column Groups

- The analysis requires:
  - Material properties, including Modulus Data (elastic and creep or consolidation parameters).
  - Stress distribution with depth.

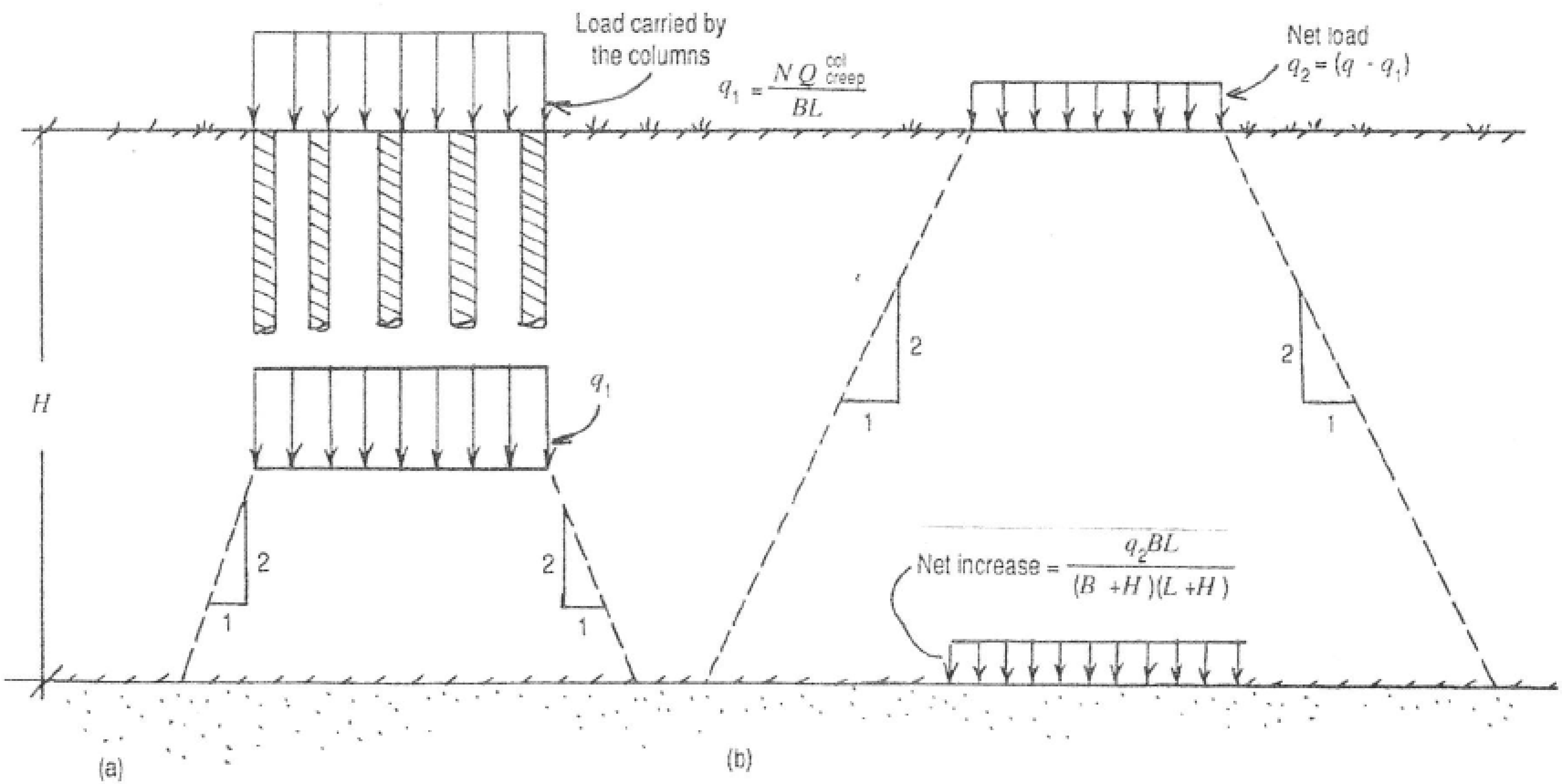
The stress distribution may be determined by:

- Elastic Theory
- Empirical methods
- Numerical methods (eg. FEM analysis)

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



Insight Provided by Broms on Stress Distribution Below Lime Column Group: (b) When stresses in columns are <u>above</u> creep strength of columns.



Application to Column Groups

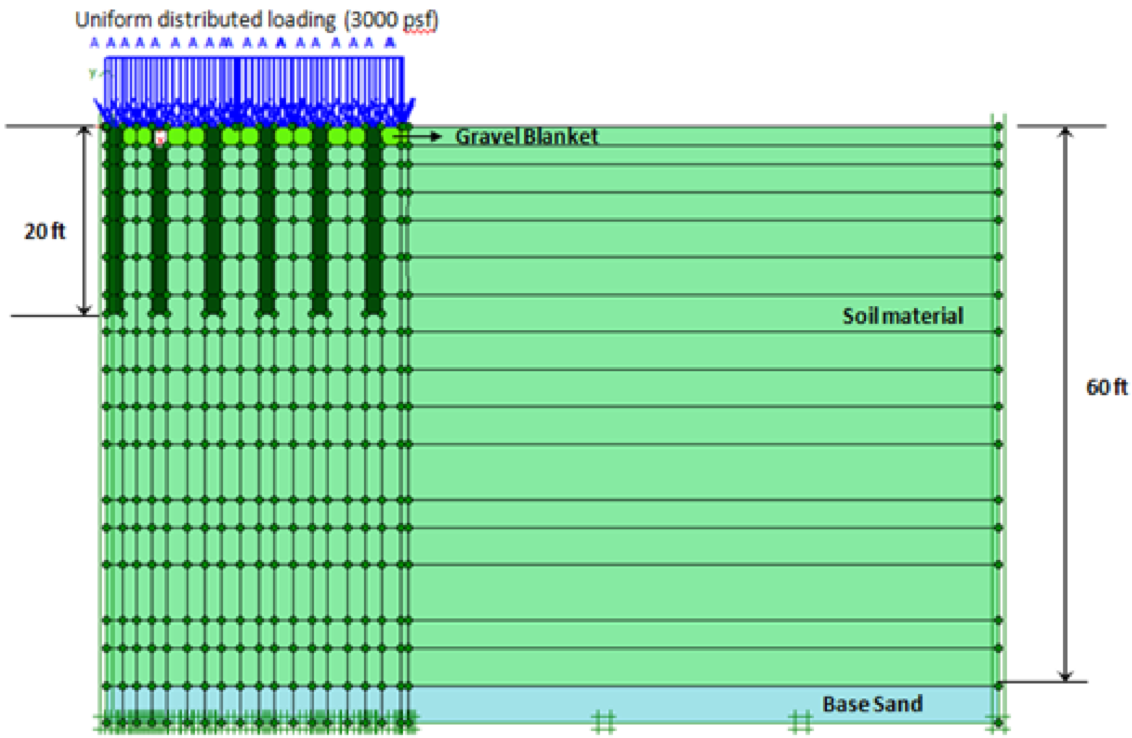
- Broms acknowledges that side shear on block can be used to reduce load transferred to base but also notes that when column stiffness is reduced and load is transferred to soil thru footing contact, then compression of Upper Zone will be greater, as the reduced stiffness of columns must be used.

- An analysis of these proposals suggests the use of the “imaginary footing” concept, with the surface load applied at a depth between 2/3L and the bottom of the 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	$c(psf)$	$\phi(\deg.)$
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

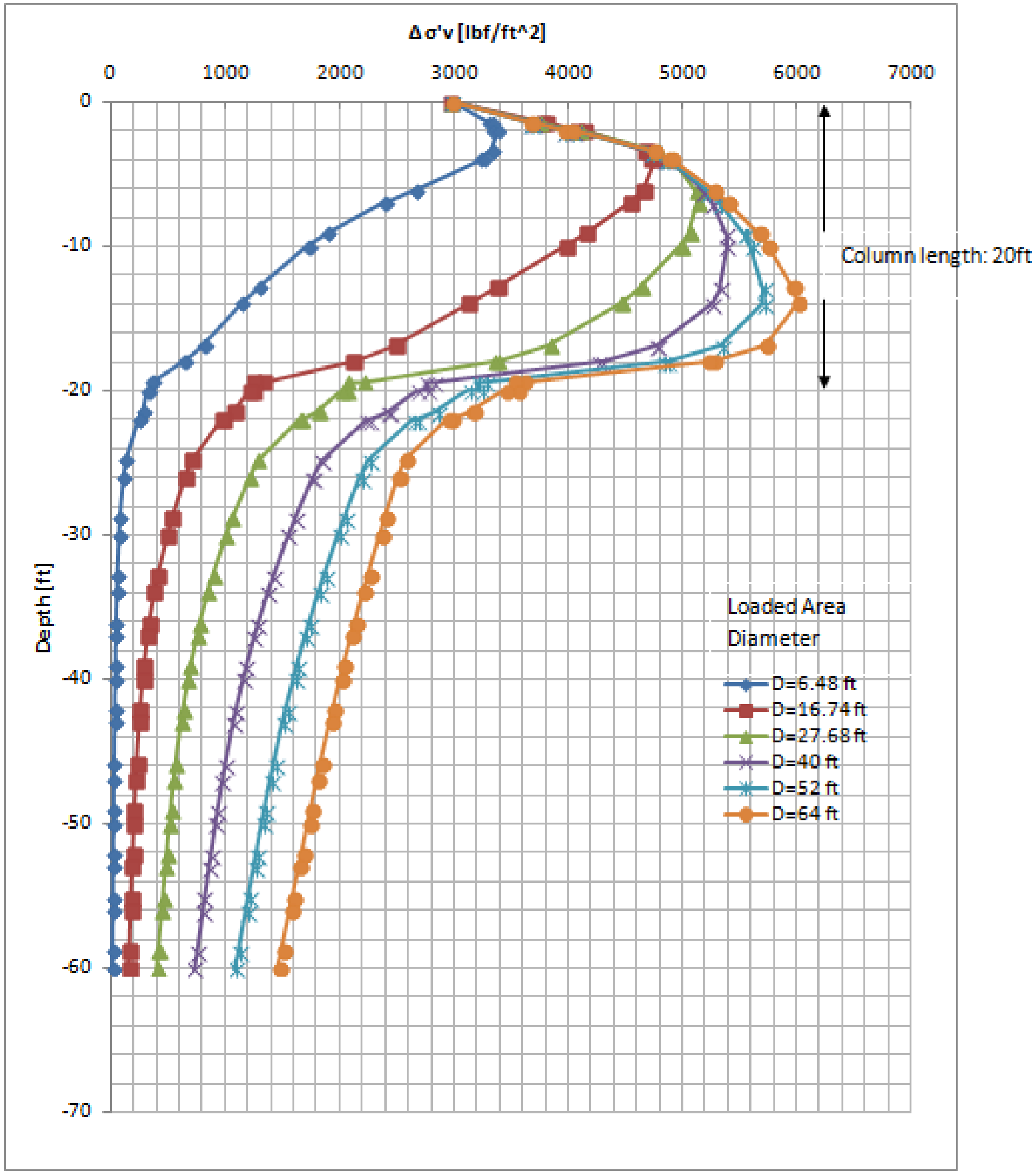
Φ soil = 30^0

Columns: E = 355 ksf

ν = 0.23

Φ stone = 45^0

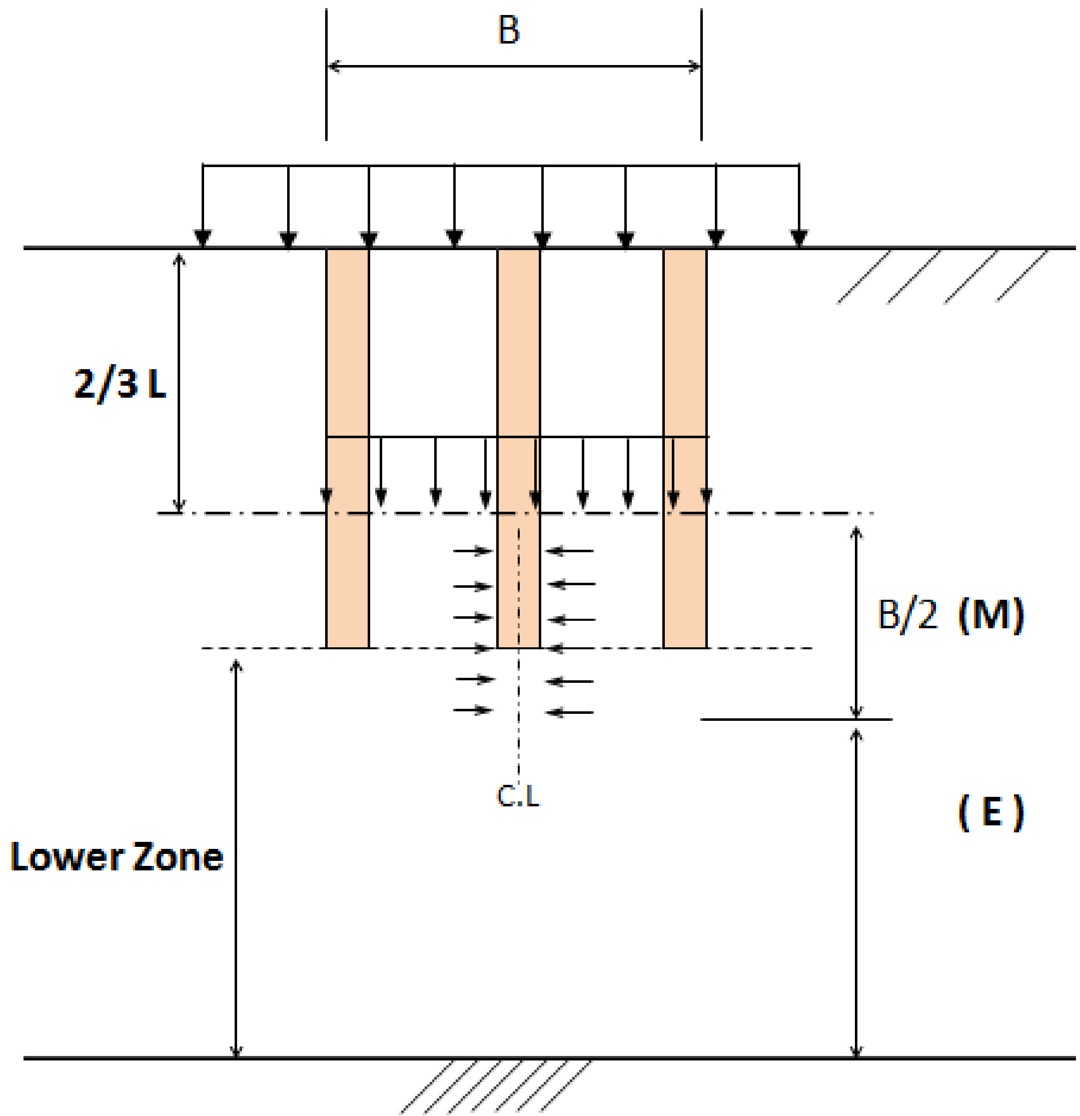
Ar = 0.29



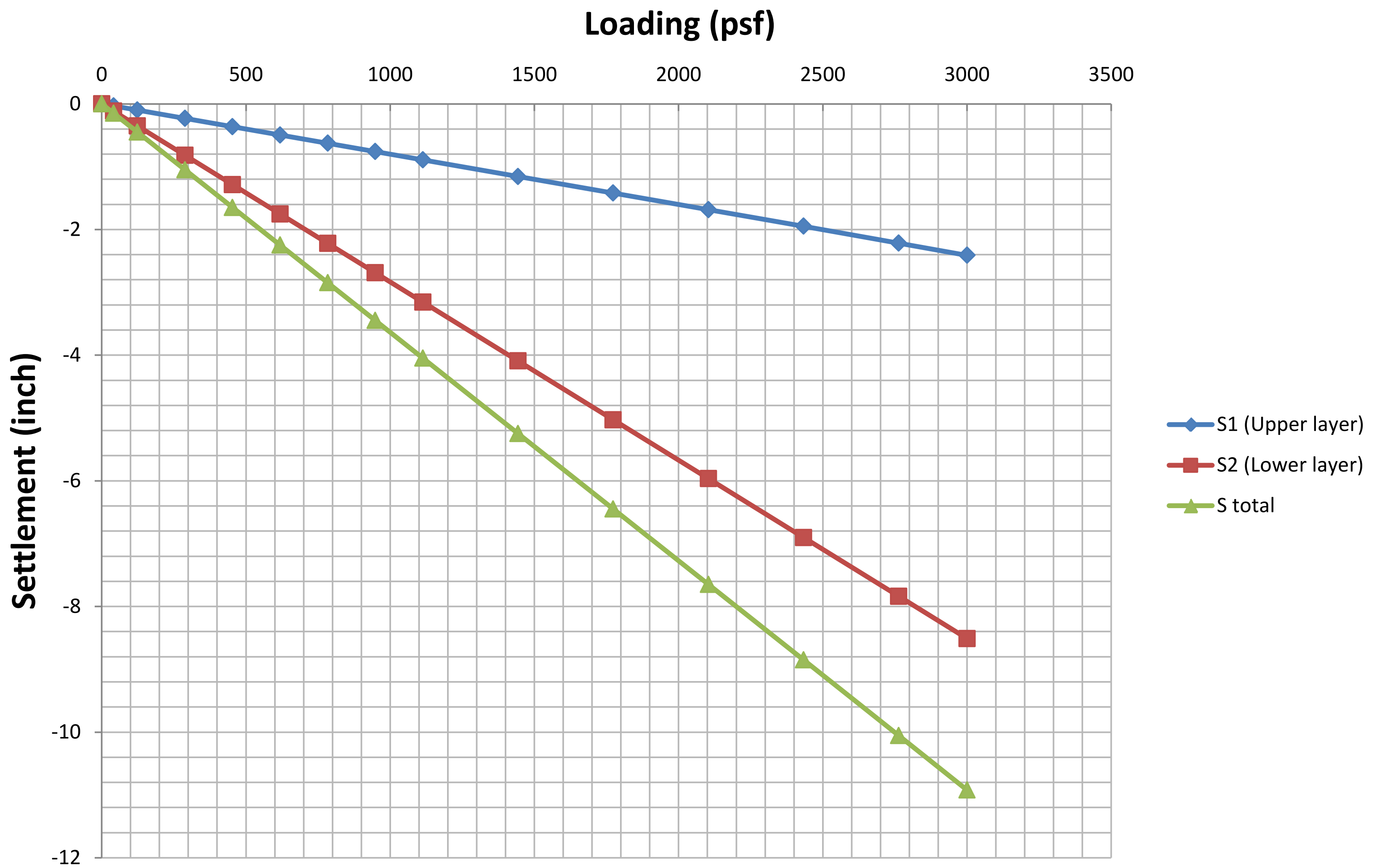
Analysis of Stress Distribution beneath Aggregate Pier Column Groups

- 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).

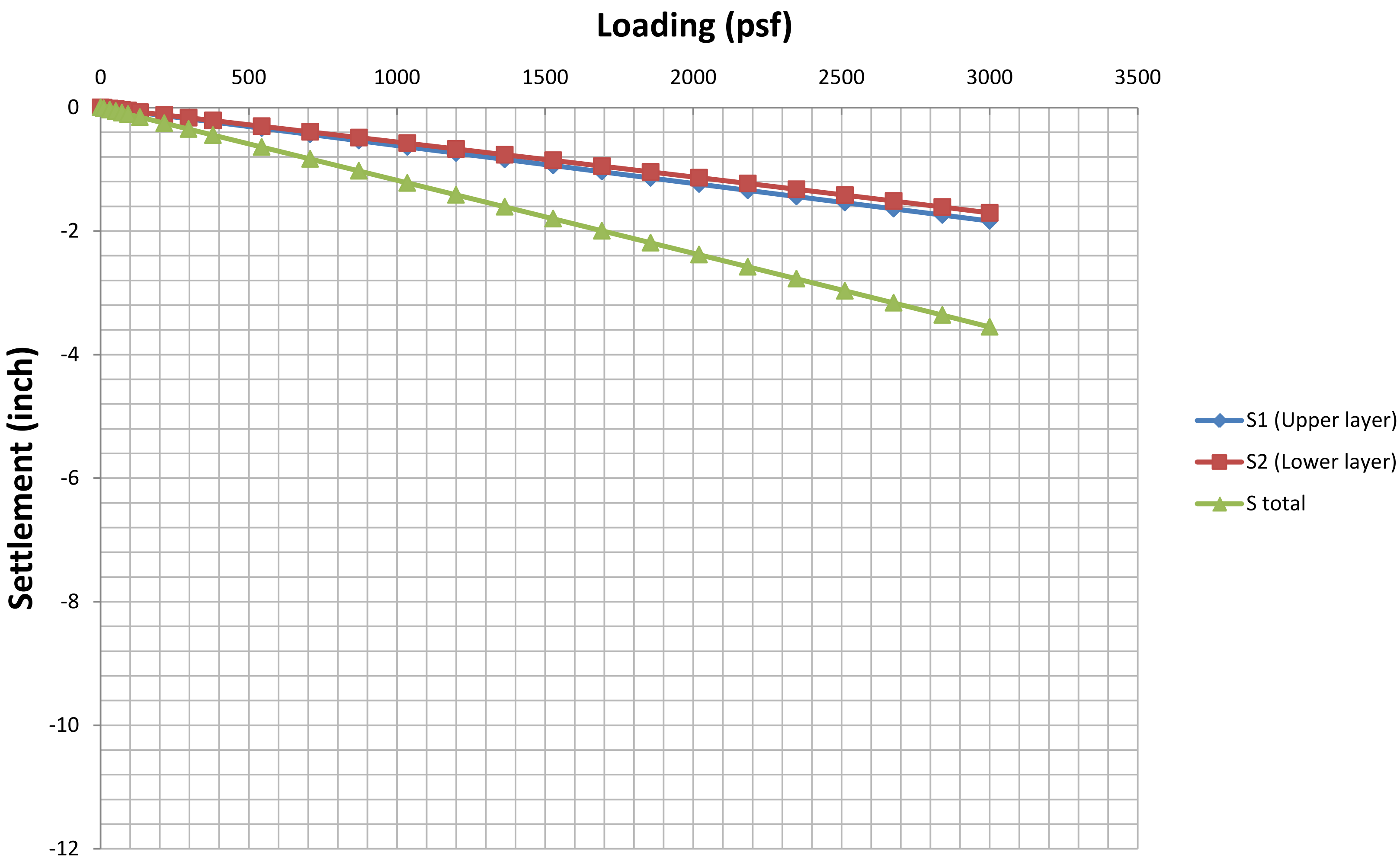
Boussinesq's solution with loading at 2/3 L



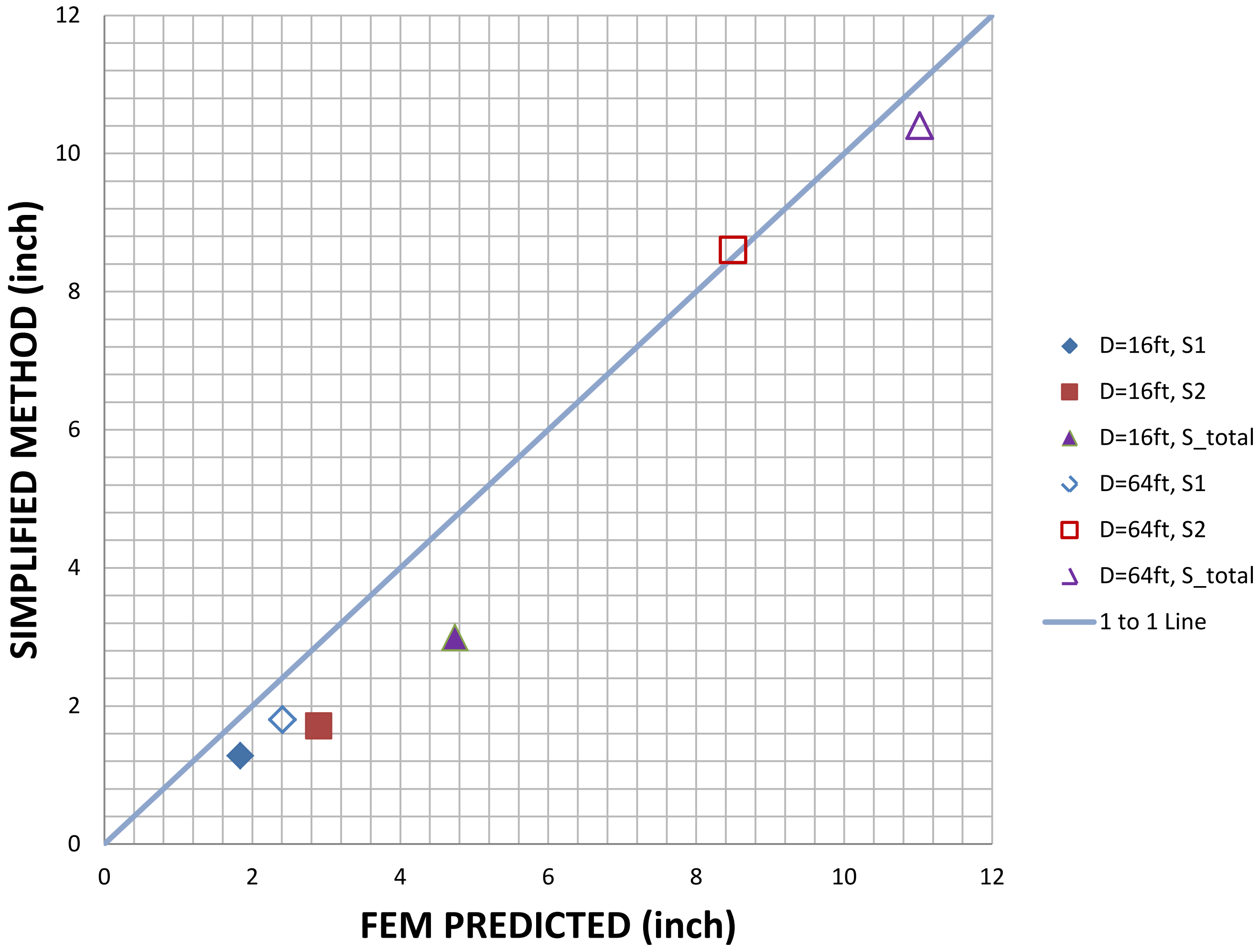
Observations from Stress Distribution Study
Settlement for D = 64ft



Observations from Stress Distribution Study
Settlement for D = 16.74ft



Comparison of Simplified Method and FEM Analysis



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.

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.