Input Parameters for the Design of Stone Columns

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Introduction

This paper summarises the presentation given at the CIRIA Core Members workshop held on 12th December 2000 as part of the introduction to the CIRIA Research Project RP604, 'Treated ground: Engineering properties and performance'. The CIRIA report provides guidance on the assessment and measurement of the properties of treated ground particularly with regard to improving the effectiveness of ground treatment techniques and assisting foundation design and construction on treated ground. This paper focuses on design aspects of just one technique for ground treatment using vibro stone columns.

Although there are a wide range of techniques used in the UK to treat ground, a significant proportion is carried out by vibro methods, usually in the form of stone columns. These methods utilise a depth vibrator that can be introduced into the ground, often to considerable depth, with the addition of well graded stone aggregate either to the top of the bore, (top feed), or via the vibrator and follower tubes to the base of the bore, (bottom feed). In granular soils the process improves the ground by densification and the reinforcing effect of the columns. In cohesive soils the improvement is primarily one of reinforcement. A full description of the vibro techniques and other treatment methods are given in the recently published CIRIA Funders Report CP/93.

Design of stone columns is considered by many people to be a 'black art'. In reality, the methods currently used have changed little since the 1970s when papers were published by Baumann and Bauer (1974), Hughes and Withers (1974) and Priebe (1976). There have been some minor tinkering with the methods such as Priebe (1988, 1995), and Watts (2000). However, most design is still based on the earlier approaches with the 'art' being the choice of input parameters and the degree of improvement imparted to the surrounding ground by vibration and densification.

Design Considerations

There are two main design considerations to be addressed when using stone columns:

- Will use of stone columns reduce potential foundation settlements to a tolerable level?

- Is there sufficient bearing capacity being provided by the stone columns?

The Baumann and Bauer (1974) method is used by the majority of specialist ground improvement contractors as justification for the reduction in potential settlement, although the method given by Priebe (1995) is used under certain circumstances.

Bearing Capacity is usually estimated using the approach given by Hughes and Withers (1974), with modifications for use in non cohesive soils.

Design for settlement reduction and bearing capacity are often based on the concept of a unit cell comprising a single column and the surrounding soil, **Figure 1**, and the concept of load share between the column and surrounding soil, **Figure 2**.

The Baumann and Bauer Method

The Baumann and Bauer method is based on a modular ratio approach where the load share between column and soil is dependent on the relative stiffness, (Young's modulus E or confined modulus D) between column and soil. The 'black art' comprises assessing the degree of improvement of granular soils during construction, choosing design parameters and, finally, adjusting column geometry to reduce the net load acting on the soil, and thus reduce the foundation settlement.

The operating equations for the Baumann and Bauer method are given in **Figure 3** where the subscript c denotes column properties and the subscript s denotes soil properties. The method requires four basic parameters; the soil stiffness Es and an earth pressure coefficient Ks usually assumed to lie between the earth pressure at rest Ko and the passive earth pressure coefficient Kp; the column stiffness Ec and an earth pressure coefficient Kc usually assumed to lie between the active earth pressure Ka and Ko, but usually taken as Ko. In most cases, Es and Ec are combined into a single parameter ratio Es/Ec. Earth pressure coefficients require knowledge of both the stone and the soil column friction angle φ'.

Most specialist contractors use values for Ks, Kc and Es/Ec shown in **Table 1**. The basis of this table is figure 6 from Baumann and Bauer. However, from even a casual reading of the paper it is clear that these values are very site specific, yet they have been applied universally across many different soil types. It should be pointed out that these parameters are not recommended.

Figure 4 shows a comparison of the Baumann and Bauer parameters with computed active, at rest and passive earth pressure coefficients based on assumed typical soil friction angles. As can be seen, there does not appear to be any logic behind the choice of Ks. However, some insights can be gleaned from consideration of how stone columns are constructed.

In loose granular soils, the depth vibrator is able to penetrate the ground under its own weight by the formation of a zone of fluidised soil around the body of the poker. In denser soils this action is helped either by pumping air or water through the depth vibrator. Maximum horizontal stress on the inner facer of the stone column bore cannot be greater than hydrostatic or Ks=1 conditions, **Figure 5**.Once the depth poker has achieved the required depth, stone is tipped into the bore from the surface or via a supply tube passing through the body of the poker. Stone is then compacted by raising and lowering the vibrator with compaction occurring due to the vertical loading, vibration and partial re-penetration effect, **Figure 6**. The maximum horizontal pressure on the interface between stone and soil is limited by the passive earth pressure such that Ks=Kp. However, where the vertical load from the vibrator is limited, the lift height excessive and re-penetration insufficient, compaction of the stone will be less and the induced horizontal earth pressure will lie somewhere between Ko and Kp.

The effect of construction in cohesive ground is somewhat different. Here, the initial penetration of the ground requires sufficient downward force from the weight of the poker or rig pull-down to overcome the shear strength of the soil to form the bore. In some cases it is necessary to use water flush or even pre-boring to penetrate firmer clays. Compaction of stone in the bore is similar to construction in granular soils with the maximum horizontal pressure limited by passive earth pressure or the cavity expansion limit pressure.

CIRIA Research Project RP604 Treated ground: engineering properties and performance

Input parameters for the design of stone columns

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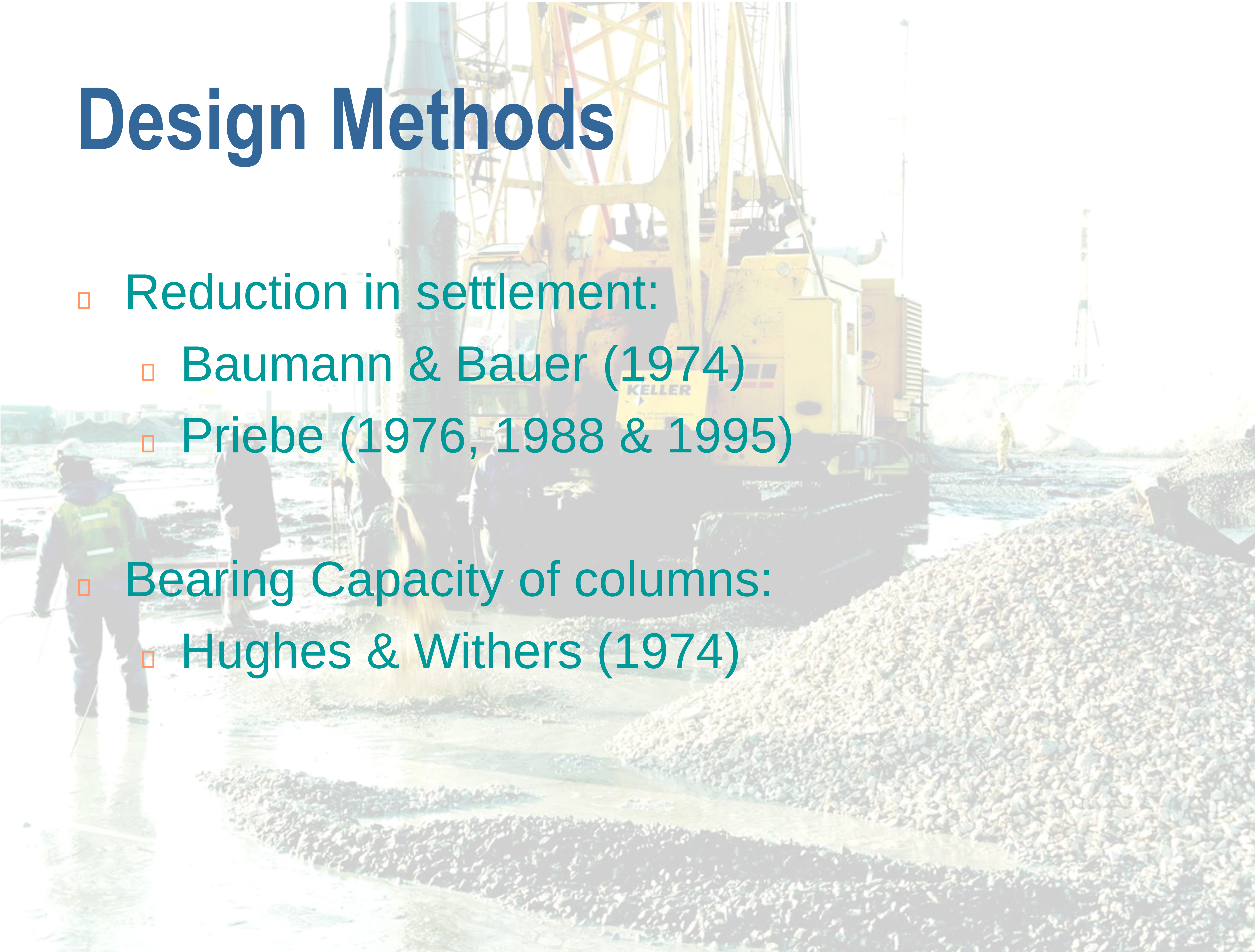
Introduction

- Significant proportion of fill treated using vibro usually in the form of stone columns
- Design is usually considered a ‘black art’
- In reality, little change since the 1970s

Design Considerations

- Will use of stone columns reduce potential settlements to a tolerable level?
- Is there sufficient bearing capacity provided by stone columns?

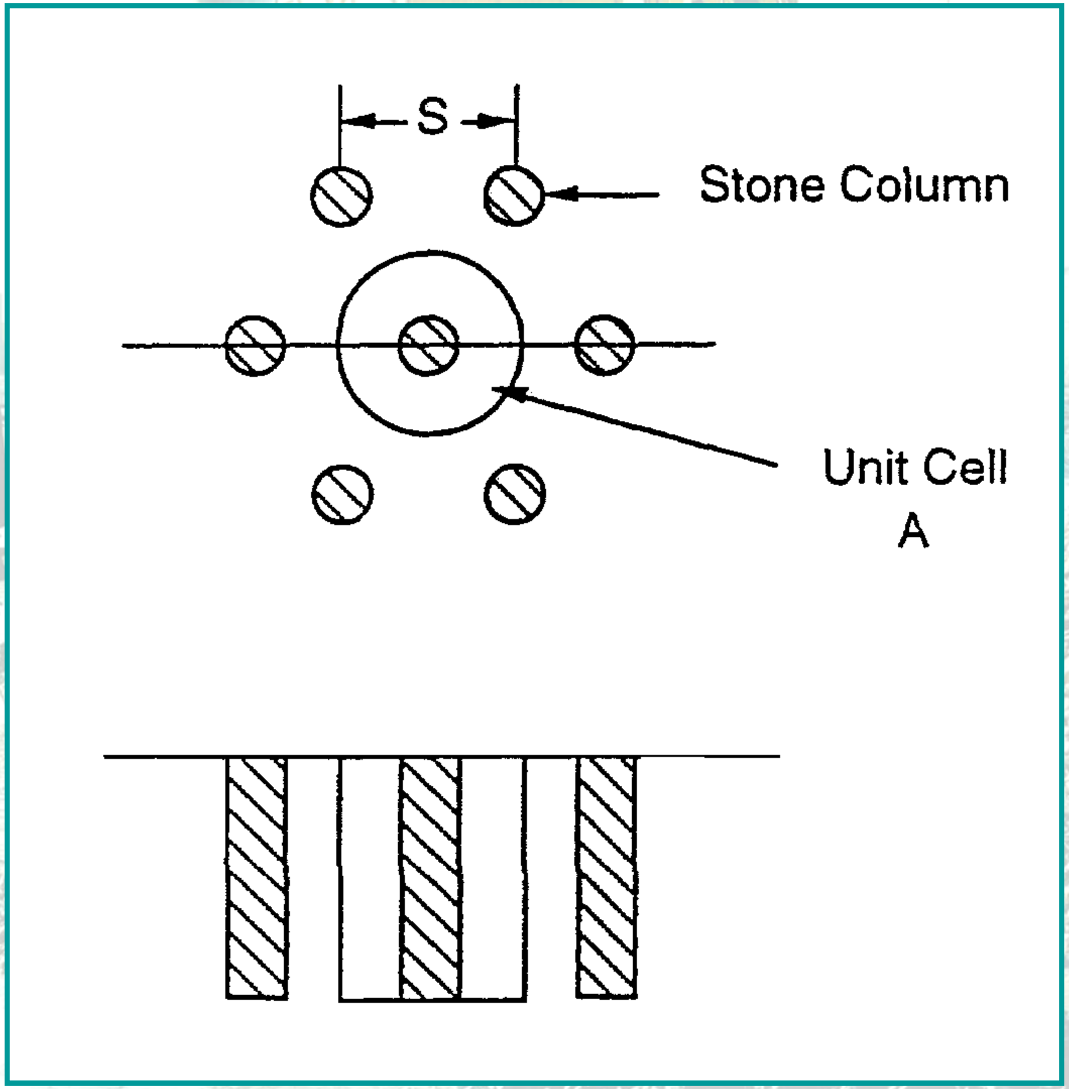
Design Methods



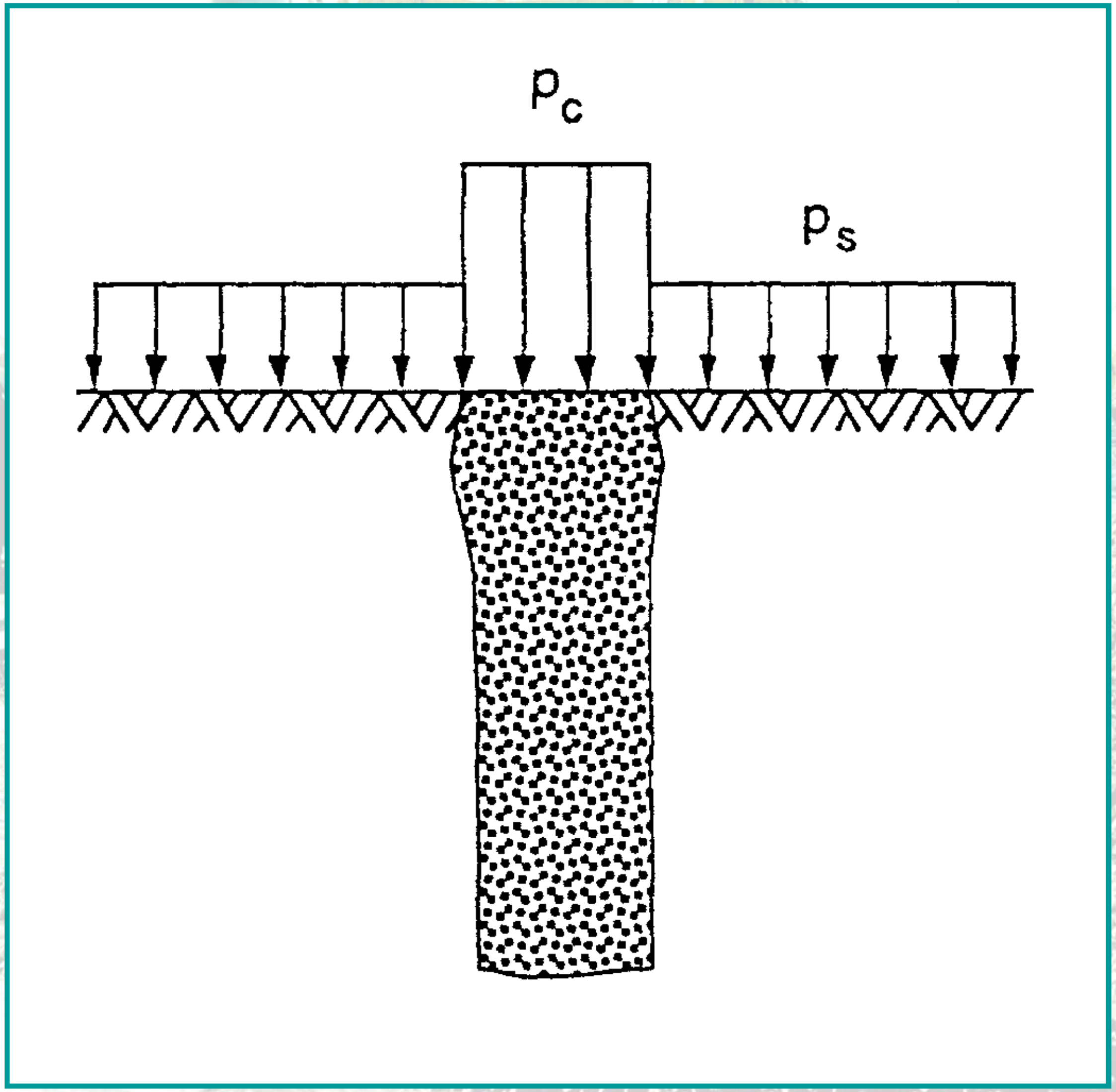
- Reduction in settlement:
  - Baumann & Bauer (1974)
  - Priebe (1976, 1988 & 1995)

- Bearing Capacity of columns:
  - Hughes & Withers (1974)

Concept of Unit Cell Area



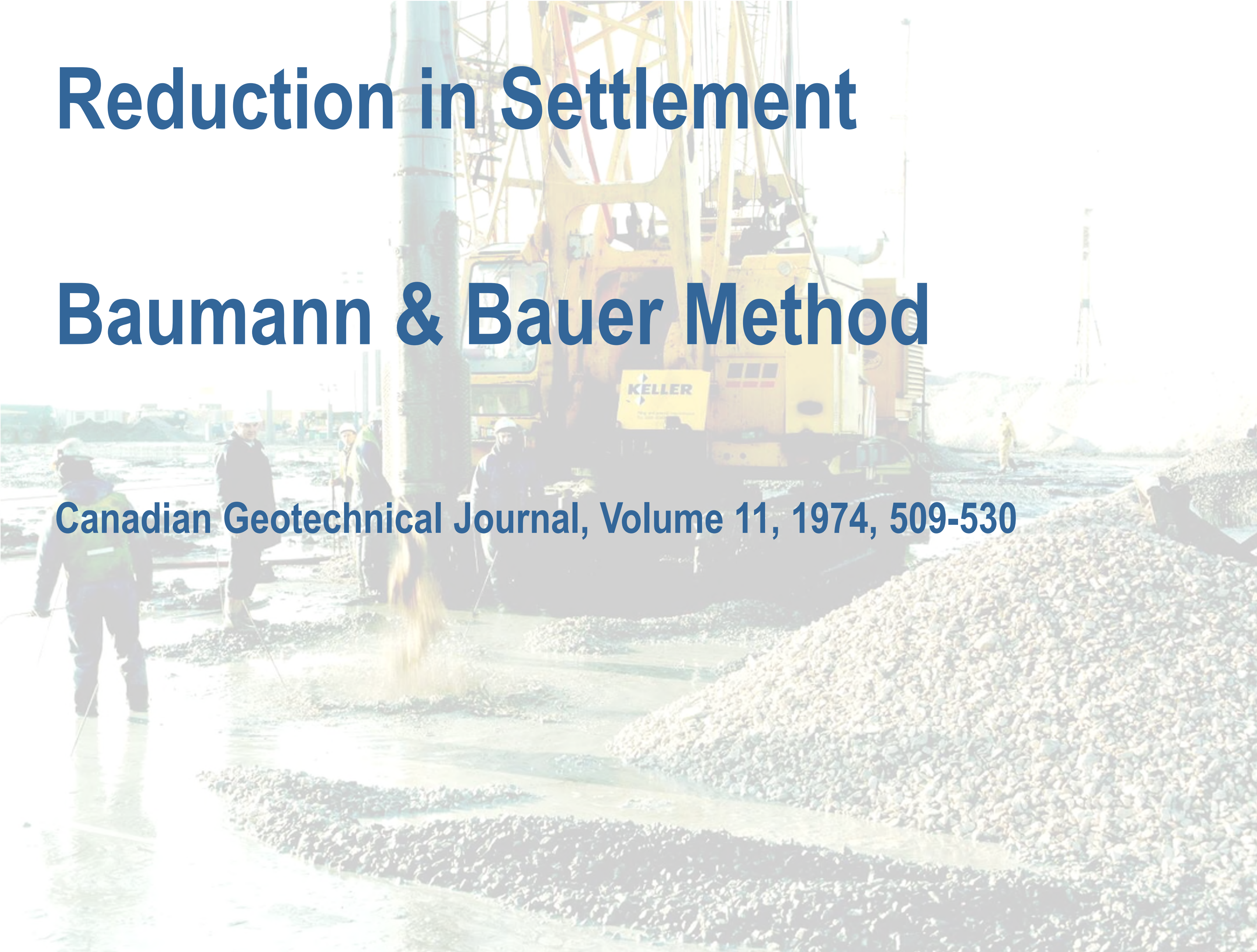
Load Share Between Column & Soil



Reduction in Settlement

Baumann & Bauer Method

Canadian Geotechnical Journal, Volume 11, 1974, 509-530



Baumann & Bauer - Equations

$$\frac{Pc}{Ps} = \frac{\left(1 + 2\frac{Es}{Ec}Ks.\ln\frac{a}{r_0}\right)}{\left(2\frac{Es}{Ec}Kc.\ln\frac{a}{r_0}\right)}$$

$$P.A = Pc.Ac + Ps.As$$

$$a = \sqrt{\frac{A}{\square}}$$

P	bearing stress
r_0	radius of the stone column
A	foundation area
K	earth pressure coefficient
E	stiffness
c	denotes column properties
s	denotes soil properties

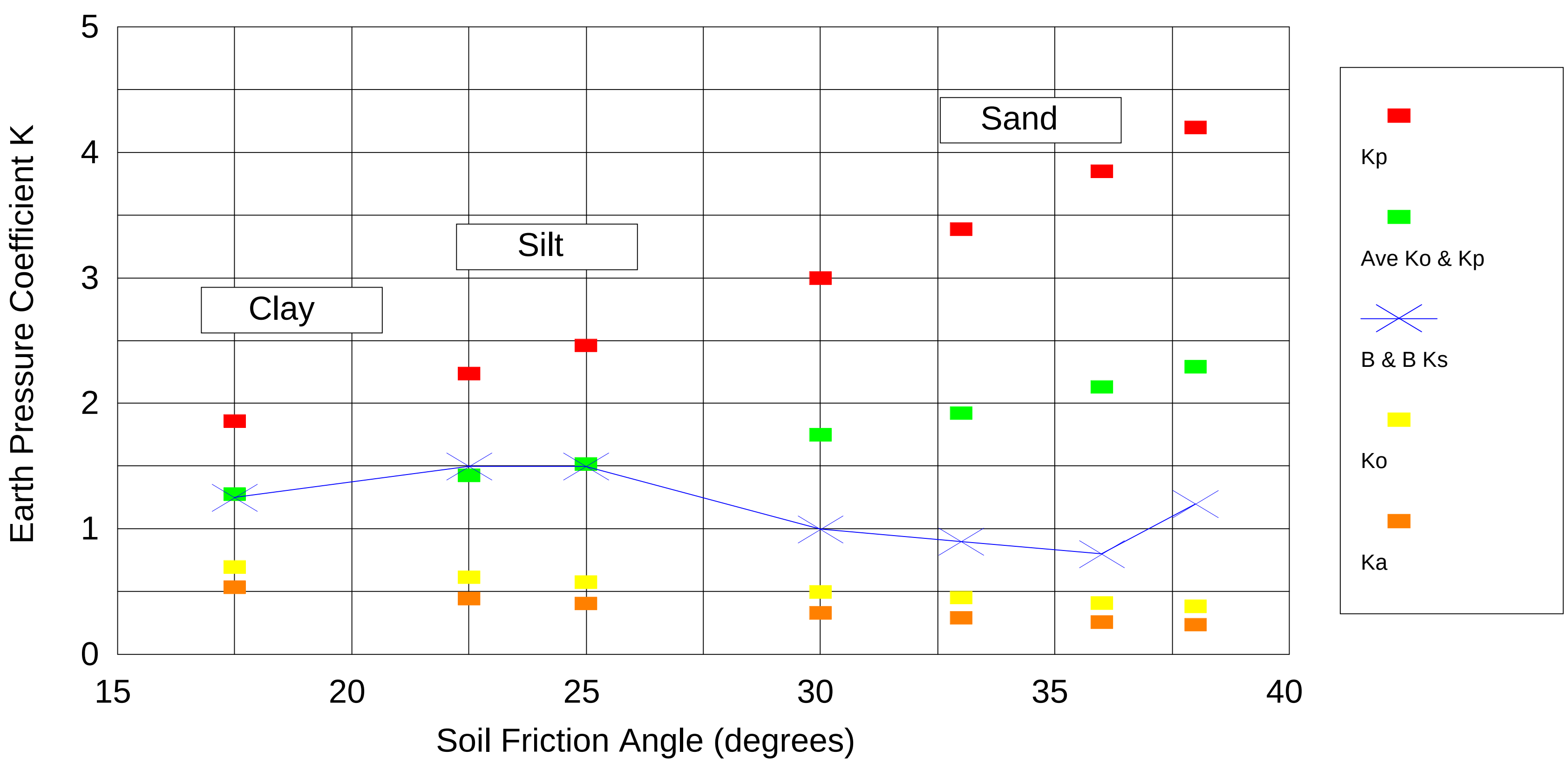
Baumann & Bauer - Key Parameters

- K_s usually assumed to lie between K_o and K_p
- K_c assumed to lie between K_a and K_o but usually taken as K_o
- f’ friction angle for soil (for K_s, K_o and K_p)
- f’ friction angle for stone column (for K_c, K_a and K_o)
- Ratio E_s/E_c

Baumann & Bauer - Key Parameters

Note that these parameters are NOT recommended	Typical Friction Angle ϕ'	Es/Ec	Earth Pressure Coefficient	
			Column Kc	Soil Ks
Dense SAND	38.0	0.5	0.40	1.20
Medium dense SAND	36.0	0.25	0.40	0.80
Loose to medium dense SAND	33.0	0.167	0.40	0.90
Loose SAND	30.0	0.083	0.40	1.00
Sandy SILT	25.0	0.125	0.60	1.50
Clayey SILT	22.5	0.063	0.60	1.50
Soft silty CLAY	17.5	0.04	0.75	1.25

Baumann & Bauer - Comparison



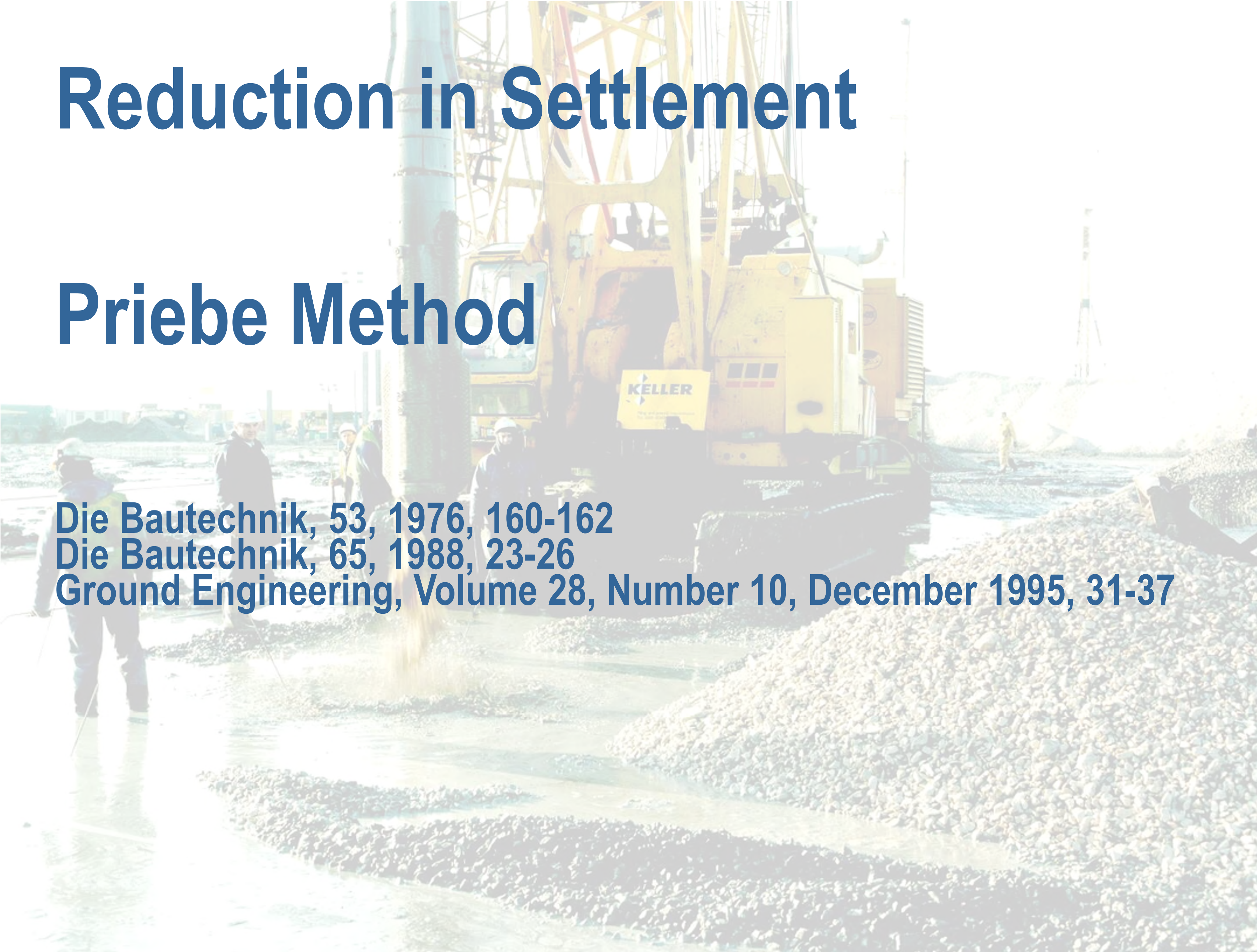
Baumann & Bauer Example

Baumann & Bauer check
Pad footing example

		Soil 1	Soil 2	
Stone column diameter		500	600	mm
Initial soil friction angle phi'		0.0	35.0	deg
Final soil friction angle phi'		0.0	37.5	deg
Soil shear strength Cu/C'		50.0	0.0	kPa
Soil Young's modulus Es		7.5	25.0	MPa
Soil Poisson's ratio v		0.5	0.2	
Earth pressure coefficient Ka		1.00	0.27	
Earth pressure coefficient Kp		1.00	3.69	
Earth pressure coefficient Ks		1.25	0.85	
Applied foundation load q		150.0	150.0	kPa
Unit area per column A		1.25	1.25	m2
Equivalent radius a		0.63	0.63	m
Stone column friction angle		40.0	40.0	deg
Stone column Young's modulus Ec		40.0	40.0	MPa
Earth pressure coefficient Kc = Ko		0.36	0.36	
Stone column spacing		1.20	1.20	m
Stone column area Ac		0.196	0.283	m2
Area ratio Ac/A		0.16	0.23	
Ratio A/Ac		6.37	4.42	
Ratio Ec/Es		5.33	1.60	
Ratio Es/Ec		0.19	0.63	
ln(a/ro)		0.93	0.74	
1+2*(Es/Ec)*Ks*ln(a/ro)		1.43	1.79	
2*(Es/Ec)*Kc*ln(a/ro)		0.12	0.33	
Pc/Ps		11.57	5.39	
Pc		652.3	405.8	kPa
Ps		56.4	75.2	kPa
Basic improvement factor n0		2.66	1.99	
Soil friction angle phi'	Ac/A	7.5	36.2	deg
Soil shear strength Cu	Ac/A	42	0	kPa

Reduction in Settlement

Priebe Method



Die Bautechnik, 53, 1976, 160-162
Die Bautechnik, 65, 1988, 23-26
Ground Engineering, Volume 28, Number 10, December 1995, 31-37

Priebe - Equations

$$n_0 = 1 + \frac{A_c}{A}\left[\frac{0.5 + f\left(\nu_s, \frac{A_c}{A}\right)}{K_{ac} \cdot f\left(\nu_s, \frac{A_c}{A}\right)} - 1\right]$$

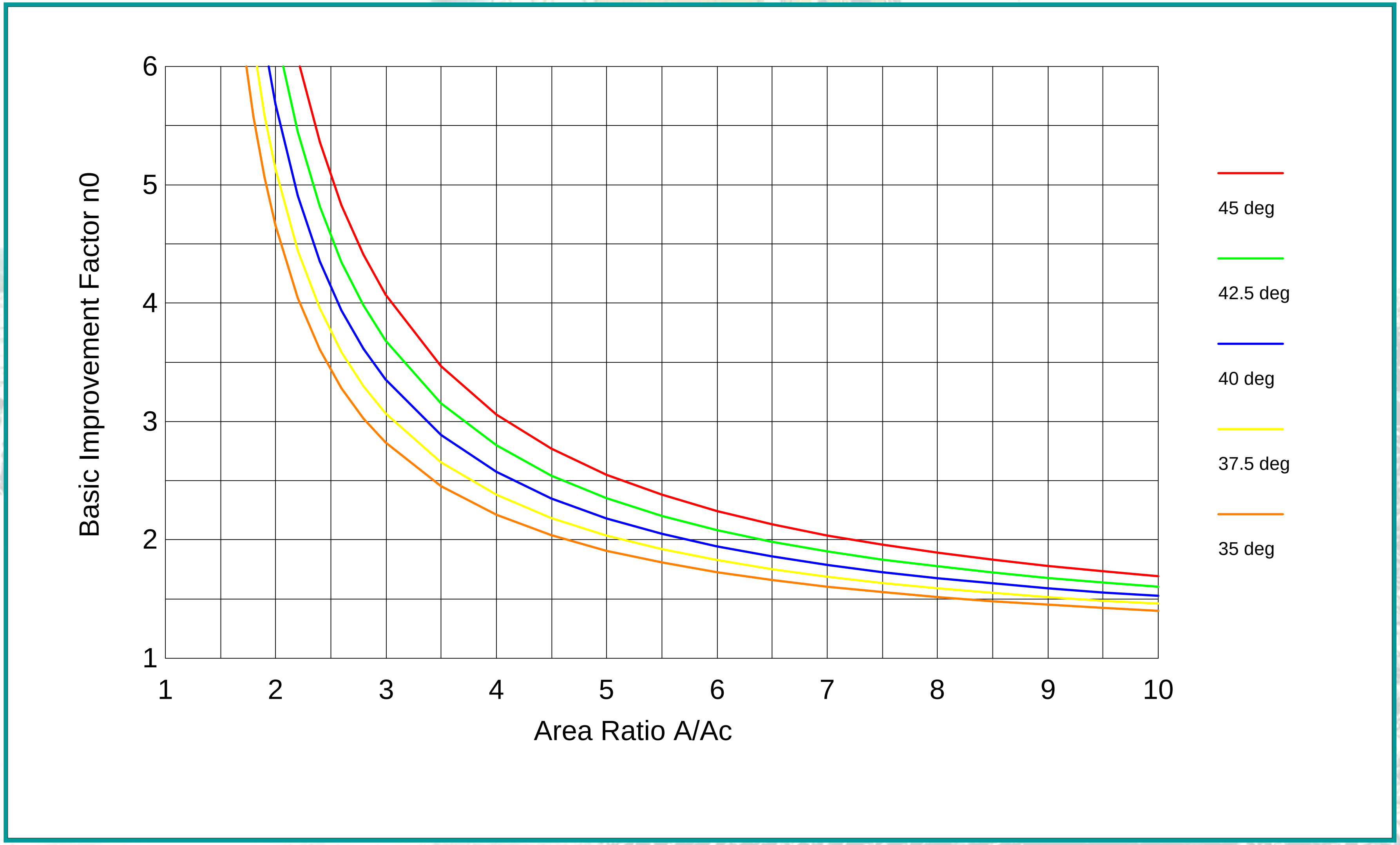
$$f\left(\nu_s, \frac{A_c}{A}\right) = \frac{1 - \nu_s^2}{1 - \nu_s - 2\nu_s^2} \frac{\left(1 - 2\nu_s\right)\left(1 - \frac{A_c}{A}\right)}{1 - 2\nu_s + \frac{A_c}{A}}$$

n_0	soil improvement
A_c	stone column area
A	foundation area
K_{ac}	active earth pressure coefficient
n_s	Poisson's ratio

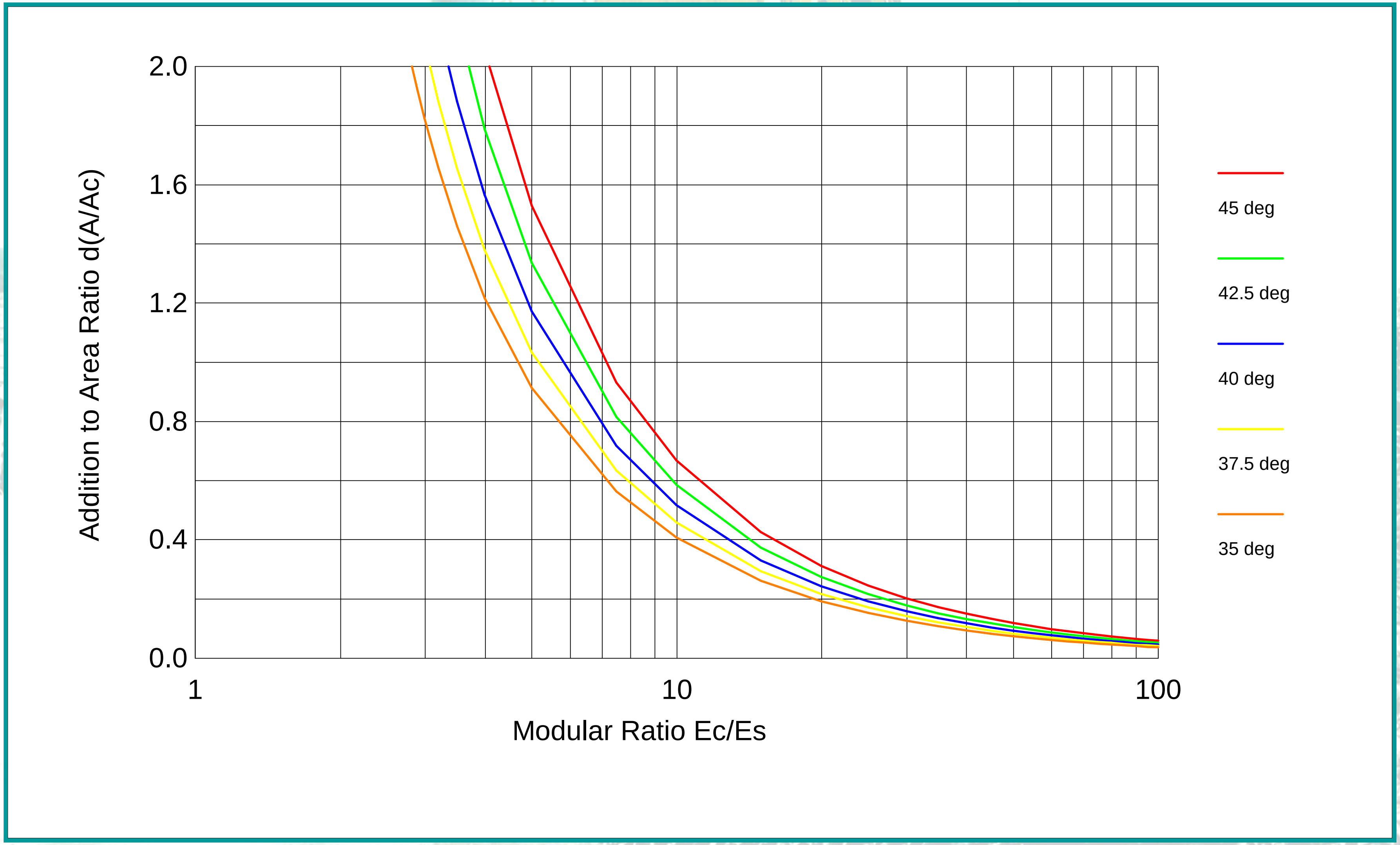
Priebe - Key Parameters

- K_{ac} active earth pressure coefficient for column
- Assumes K_o equal to 1 for soil
- f' friction angle for stone column
- Ratio E_c/E_s
- Poisson's Ratio n_s for soil

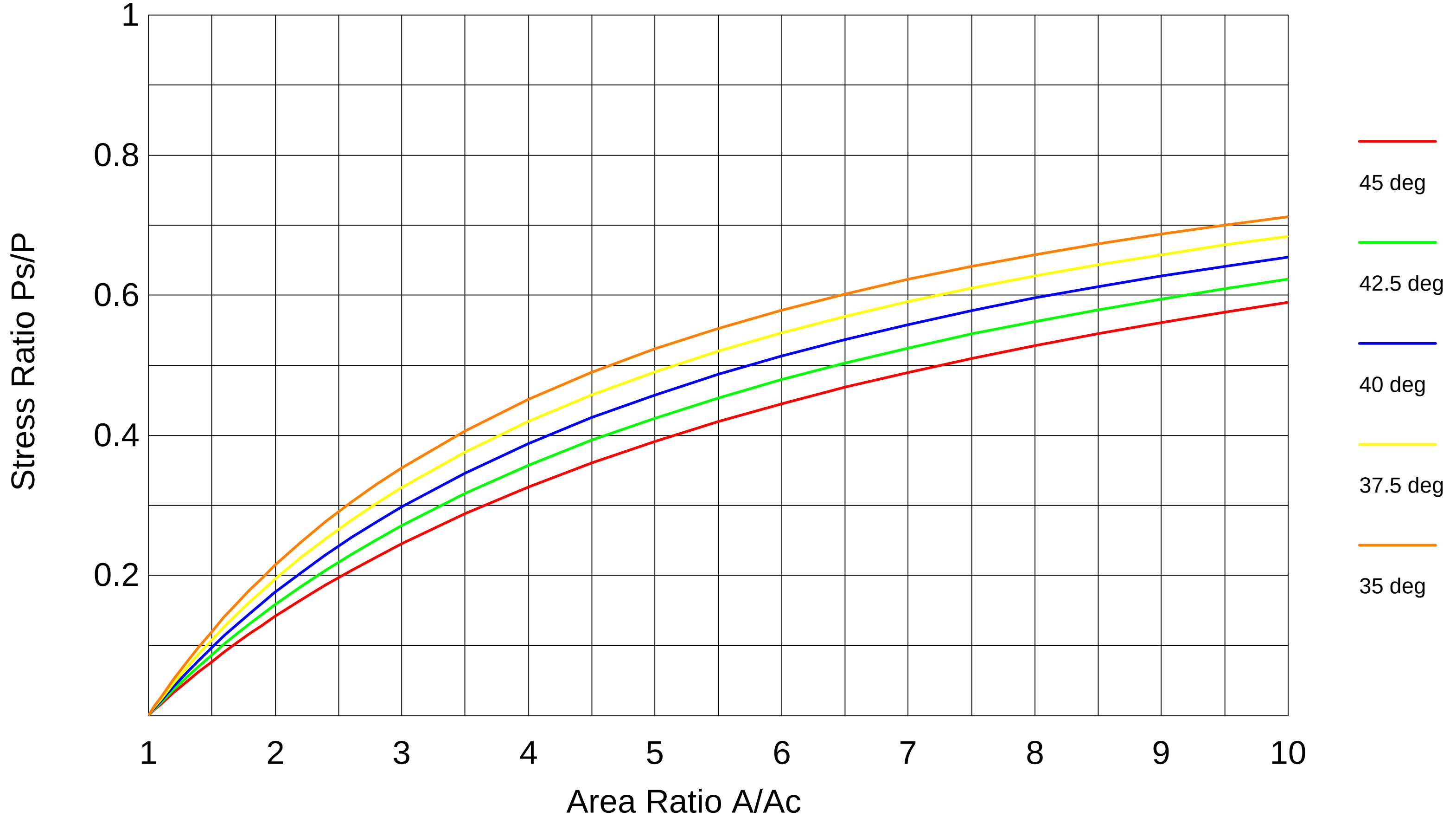
Priebe - Basic Improvement n_0



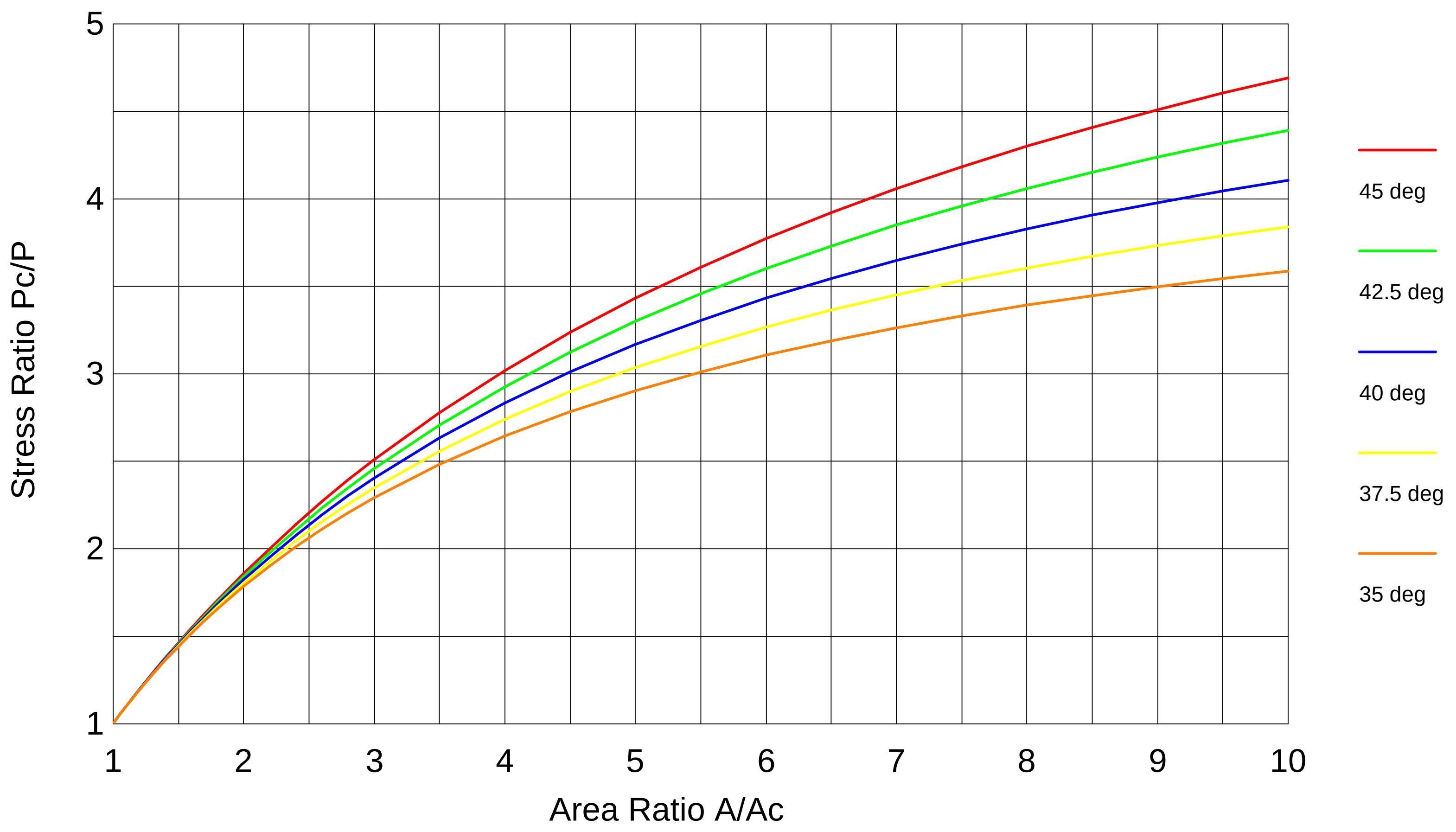
Priebe - Correction for E_c/E_s



Priebe - Soil Stress P_s



Priebe - Column Stress P_c



Priebe Example

Priebe check
Pad footing example

	Soil 1	Soil 2	
Stone column diameter	500	600	mm
Average vertical effective stress	15.0	40.0	kPa
Initial soil friction angle phi'	0.0	37.5	deg
Final soil friction angle phi'	0.0	38.8	deg
Soil shear strength Cu/C'	50.0	0.0	kPa
Soil Young's modulus Es	7.5	25.0	MPa
Soil Poisson's ratio v	0.2	0.2	
Applied foundation load q	150.0	150.0	kPa
Unit area per column A	1.25	1.25	m2
Stone column friction angle	40.0	40.0	deg
Stone column Young's modulus Ec	40.0	40.0	MPa
Earth pressure coefficient Kc = Ka	0.22	0.22	
Earth pressure coefficient Kc = Ko	0.36	0.36	
Stone column spacing	1.20	1.20	m
Stone column area Ac	0.196	0.283	m2
Area ratio Ac/A	0.16	0.23	
Ratio A/Ac	6.37	4.42	
Ratio Ec/Es	5.33	1.60	
f(v,Ac/A)	0.89	0.75	
Pc/Ps	7.18	7.67	
Pc	546.5	458.6	kPa
Ps	76.1	59.8	kPa
Basic improvement factor n0	1.97	2.51	

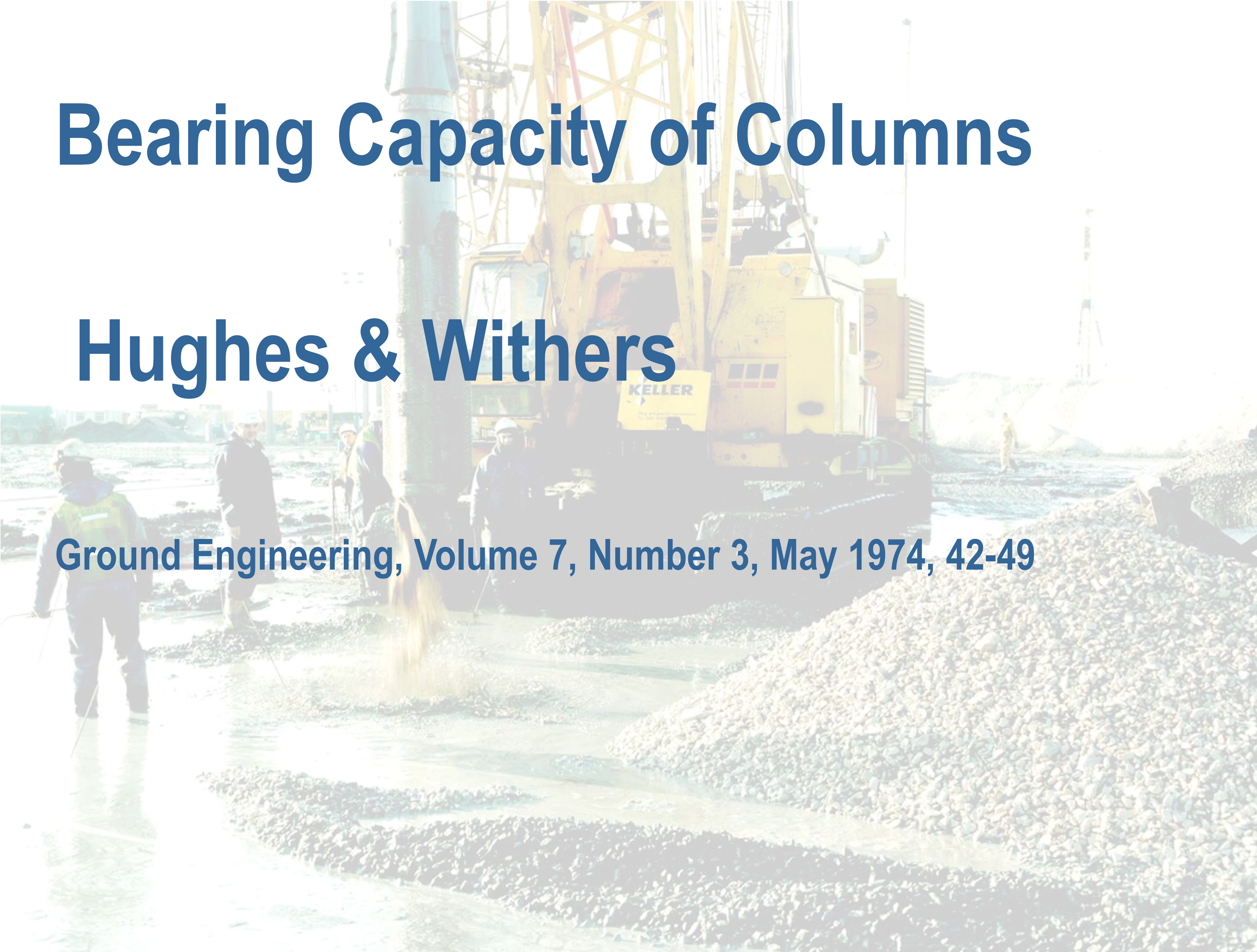
Priebe check
Pad footing example

		Soil 1	Soil 2	
Root 1 - take min +ve		0.46	0.10	
Root 2		12.86	8.07	
(Ac/A)1		0.46	0.10	
Additional area ratio d(A/Ac)		1.15	8.75	
increased area ratio A/Ac + d(A/Ac)		7.52	13.17	
(Ac/A + d(Ac/A))1		0.13	0.08	
f(v,Ac/A)		0.95	1.09	
Pc/Ps		7.03	6.70	
Pc		585.1	701.5	kPa
Ps		83.2	104.7	kPa
Improvement factor n1		1.80	1.43	
Proportional load factor m		0.52	0.36	
Proportional load factor m'		0.45	0.30	
Soil friction angle phi'	Ac/A	23.5	38.4	deg
Soil shear strength Cu	Ac/A	43	0	kPa
Soil friction angle phi'	m'	20.5	38.3	deg
Soil shear strength Cu	m'	28	0	kPa

Bearing Capacity of Columns

Hughes & Withers

Ground Engineering, Volume 7, Number 3, May 1974, 42-49



Hughes & Withers

$$P_c = K_{pc}(K_s . \sigma_v' + 4c_u)$$

Pc	stress on top of column
K_{pc}	column passive earth pressure coefficient
K_s	soil earth pressure coefficient
c_u	Undrained shear strength

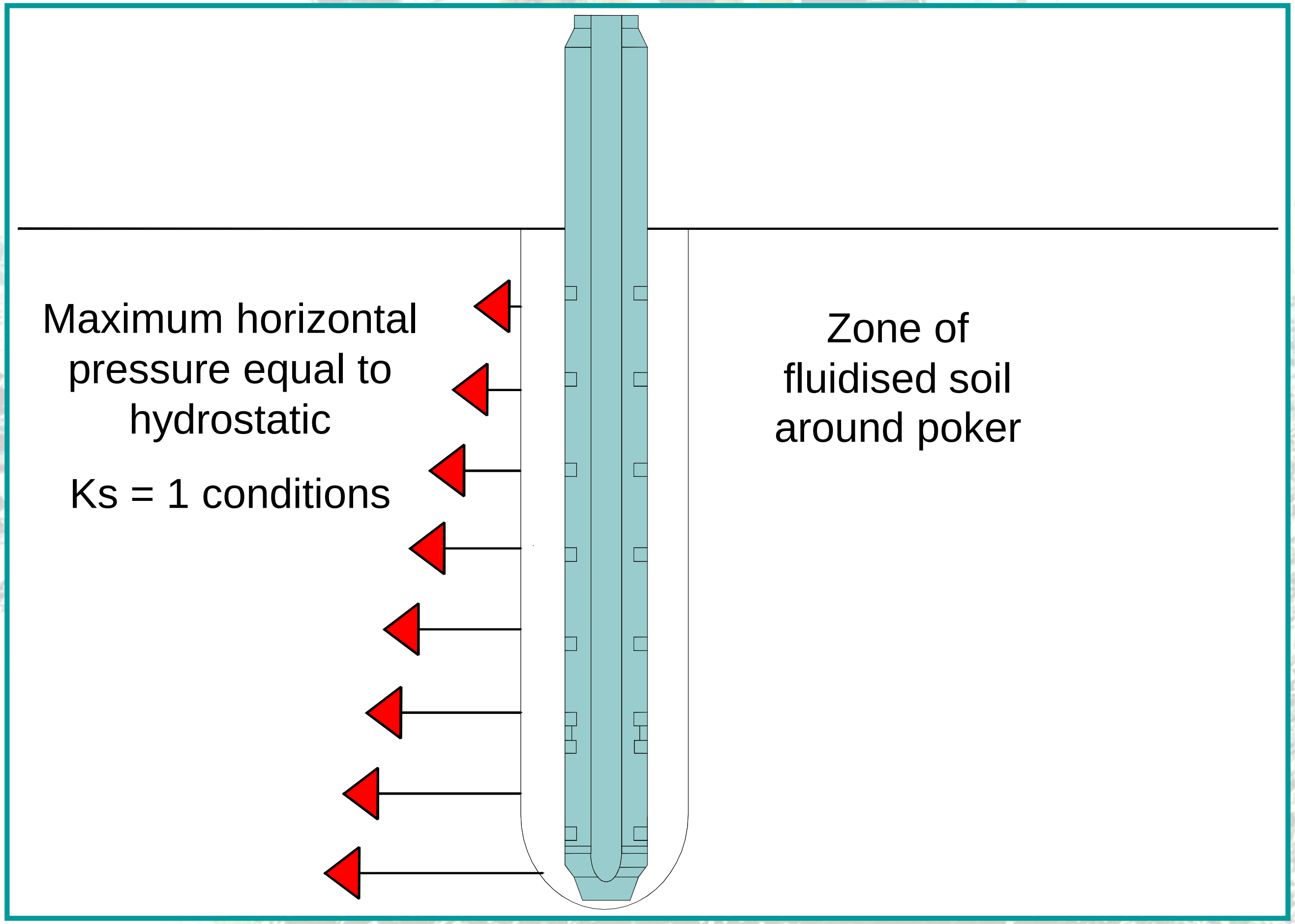
K_s usually taken as 1 in clays or K_p in granular soils

Hughes & Withers - Key Parameters

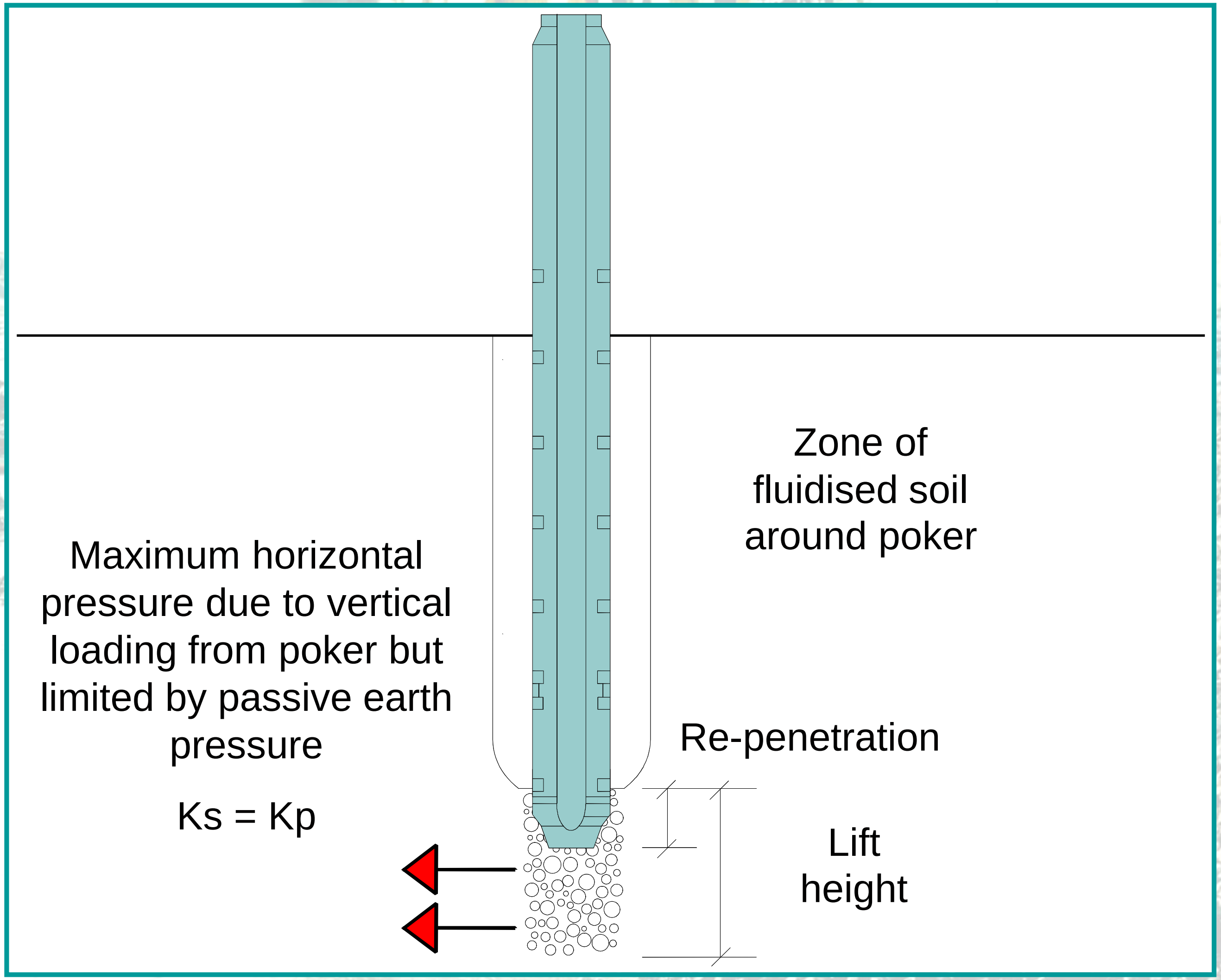
- K_{pc} passive earth pressure coefficient for column
- K_s assumed to lie between K_o and K_p
- K_s usually taken as 1 for clays or K_p for sands
- f’ friction angle for both stone column and soil
- Undrained shear strength c_u of soil
- Vertical effective stress $s_v^{/}$ in soil

Construction Issues and the Effect on Choice of Design Parameters

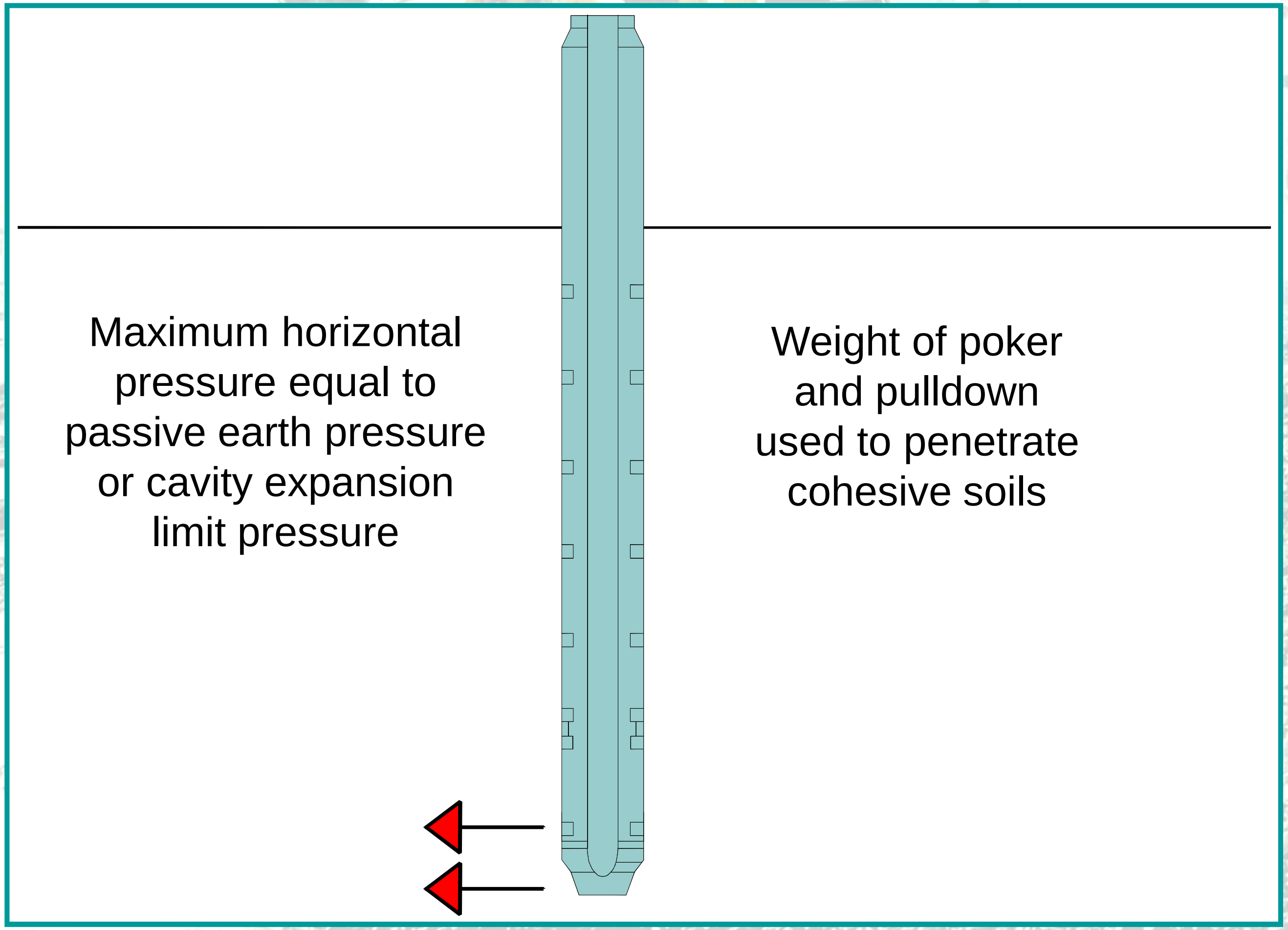
Penetration into Sands



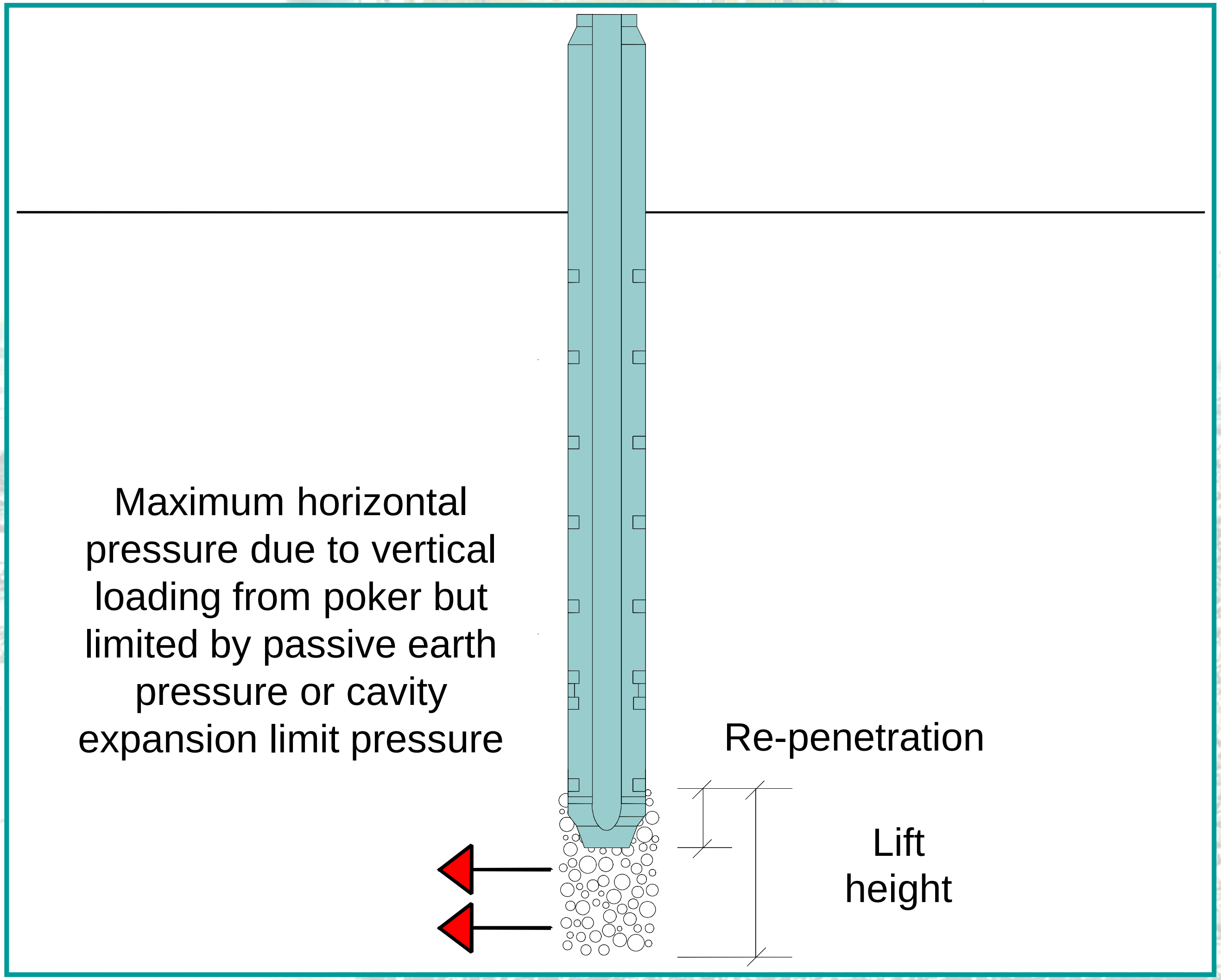
Construction of Column in Sand



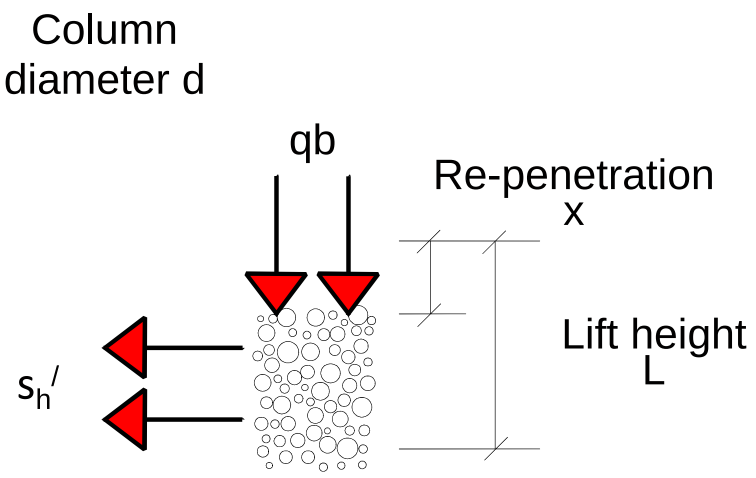
Penetration into Clays



Construction of Column in Clay



Compaction of Stone Column



$$s_h^{/} = n_s\, q_b\, d/(L-x)$$

Note

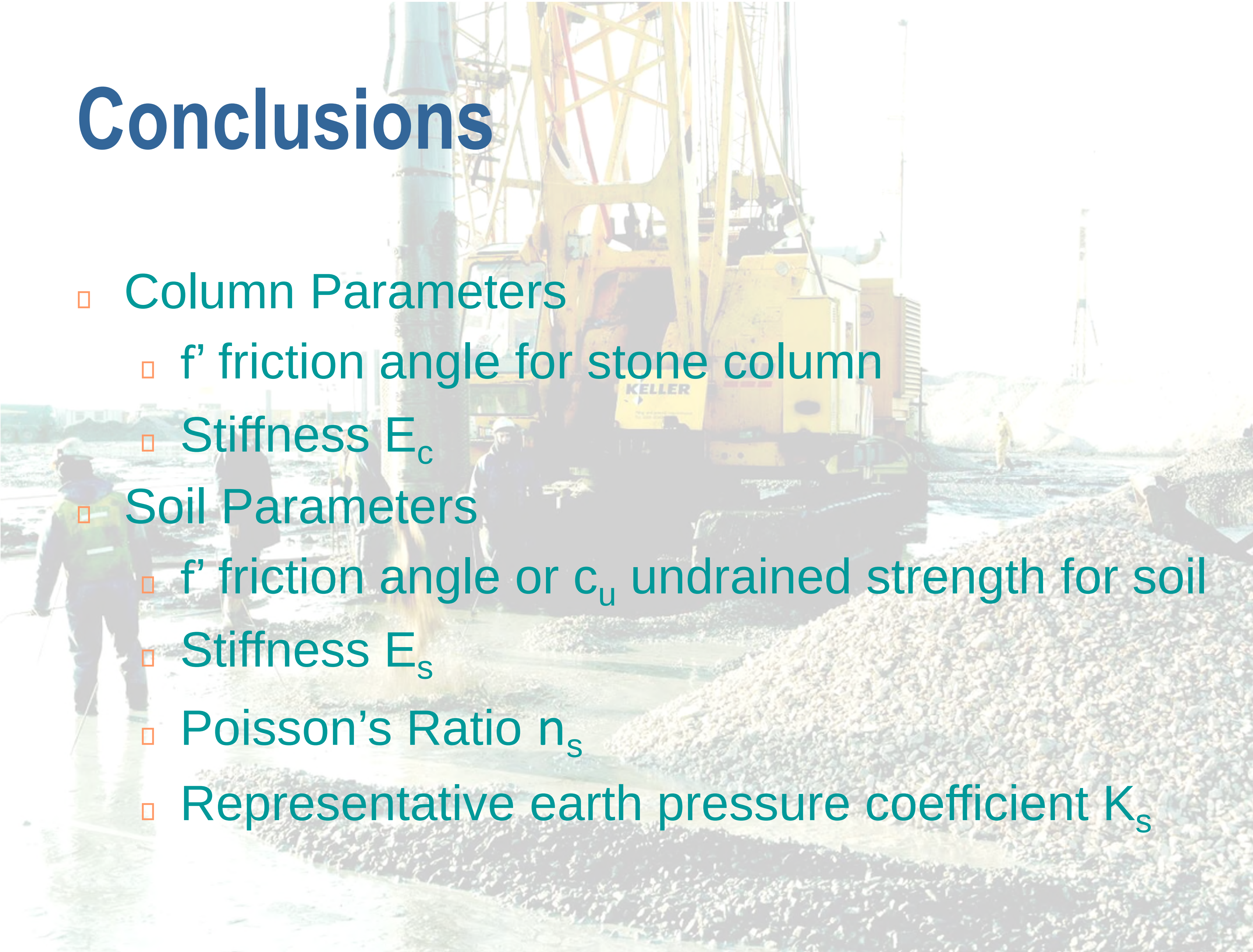
q_b is the maximum applied end bearing pressure on the base of the poker

$s_h^{/}$ cannot exceed the passive earth pressure or cavity expansion limit pressure

Ratio d/(L-x) typically 0.4 to 0.6

Poisson's Ratio n_s typically 0.2

Conclusions



- Column Parameters
  - f’ friction angle for stone column
  - Stiffness E_c
- Soil Parameters
  - f’ friction angle or c_u undrained strength for soil
  - Stiffness E_s
  - Poisson’s Ratio n_s
  - Representative earth pressure coefficient K_s

Conclusions

- Column Parameters
  - Little evidence for usual design values
  - Need quality test results
- Soil Parameters
  - Friction angle and stiffness rarely measured
  - Representative K_s needs quality test results