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 $K_o$ and $K_p$.

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)

- 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

\[
\frac{P_c}{P_s} = \frac{\left(1 + 2 \frac{E_s}{E_c} K_{s,l} \ln \frac{a}{r_0}\right)}{\left(2 \frac{E_s}{E_c} K_{c,l} \ln \frac{a}{r_0}\right)}
\]

\[P \cdot A = P_c \cdot A_c + P_s \cdot A_s\]

\[a = \sqrt{\frac{A}{\pi}}\]

- \(P\) 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 $K_0$
- $f'$ 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

<table>
<thead>
<tr>
<th>Note that these parameters are NOT recommended</th>
<th>Typical Friction Angle $\phi'$</th>
<th>$\frac{E_s}{E_c}$</th>
<th>Earth Pressure Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense SAND</td>
<td>38.0</td>
<td>0.5</td>
<td>0.40</td>
</tr>
<tr>
<td>Medium dense SAND</td>
<td>36.0</td>
<td>0.25</td>
<td>0.40</td>
</tr>
<tr>
<td>Loose to medium dense SAND</td>
<td>33.0</td>
<td>0.167</td>
<td>0.40</td>
</tr>
<tr>
<td>Loose SAND</td>
<td>30.0</td>
<td>0.083</td>
<td>0.40</td>
</tr>
<tr>
<td>Sandy SILT</td>
<td>25.0</td>
<td>0.125</td>
<td>0.60</td>
</tr>
<tr>
<td>Clayey SILT</td>
<td>22.5</td>
<td>0.063</td>
<td>0.60</td>
</tr>
<tr>
<td>Soft silty CLAY</td>
<td>17.5</td>
<td>0.04</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Baumann & Bauer - Comparison

![Graph showing Soil Friction Angle (degrees) vs. Earth Pressure Coefficient K for Sand, Silt, and Clay with various symbols representing different values.]
## Baumann & Bauer Example

### Baumann & Bauer check

**Pad footing example**

<table>
<thead>
<tr>
<th>Soil</th>
<th>Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Soil 1</th>
<th>Soil 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone column diameter</td>
<td>500 mm</td>
<td>600 mm</td>
</tr>
<tr>
<td>Initial soil friction angle φ'</td>
<td>0.0</td>
<td>35.0 deg</td>
</tr>
<tr>
<td>Final soil friction angle φ'</td>
<td>0.0</td>
<td>37.5 deg</td>
</tr>
<tr>
<td>Soil shear strength Cu/C</td>
<td>50.0 kPa</td>
<td>0.0 kPa</td>
</tr>
<tr>
<td>Soil Young's modulus Es</td>
<td>7.5 MPa</td>
<td>25.0 MPa</td>
</tr>
<tr>
<td>Soil Poisson's ratio v</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Earth pressure coefficient Ka</td>
<td>1.00</td>
<td>0.27</td>
</tr>
<tr>
<td>Earth pressure coefficient Kp</td>
<td>1.00</td>
<td>3.69</td>
</tr>
<tr>
<td>Earth pressure coefficient Ks</td>
<td>1.25</td>
<td>0.65</td>
</tr>
<tr>
<td>Applied foundation load q</td>
<td>150.0 kPa</td>
<td>150.0 kPa</td>
</tr>
<tr>
<td>Unit area per column A</td>
<td>1.25 m²</td>
<td>1.25 m²</td>
</tr>
<tr>
<td>Equivalent radius r</td>
<td>0.63 m</td>
<td>0.63 m</td>
</tr>
<tr>
<td>Stone column friction angle</td>
<td>40.0 deg</td>
<td>40.0 deg</td>
</tr>
<tr>
<td>Stone column Young's modulus Ec</td>
<td>40.0 MPa</td>
<td>40.0 MPa</td>
</tr>
<tr>
<td>Earth pressure coefficient Kc = Ko</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>Stone column spacing</td>
<td>1.20 m</td>
<td>1.20 m</td>
</tr>
<tr>
<td>Stone column area Ac</td>
<td>0.196 m²</td>
<td>0.283 m²</td>
</tr>
<tr>
<td>Area ratio Ac/A</td>
<td>0.16</td>
<td>0.23</td>
</tr>
<tr>
<td>Ratio A/Ac</td>
<td>6.37</td>
<td>4.42</td>
</tr>
<tr>
<td>Ratio Ec/Ec</td>
<td>5.33</td>
<td>1.60</td>
</tr>
<tr>
<td>Ratio Es/Ec</td>
<td>0.19</td>
<td>0.63</td>
</tr>
<tr>
<td>ln(a/ro)</td>
<td>0.93</td>
<td>0.74</td>
</tr>
<tr>
<td>1+2*(Es/Ec)<em>Kc</em>ln(a/ro)</td>
<td>1.43</td>
<td>1.79</td>
</tr>
<tr>
<td>2*(Es/Ec)<em>Kc</em>ln(a/ro)</td>
<td>0.12</td>
<td>0.33</td>
</tr>
<tr>
<td>Pc/Pa</td>
<td>11.57 kPa</td>
<td>5.39 kPa</td>
</tr>
<tr>
<td>Pc</td>
<td>652.3 kPa</td>
<td>405.8 kPa</td>
</tr>
<tr>
<td>Ps</td>
<td>56.4 kPa</td>
<td>75.2 kPa</td>
</tr>
</tbody>
</table>

| Basic improvement factor n0                           | 2.66   | 1.99   |

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ac/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil friction angle φ'</td>
<td>7.5</td>
</tr>
<tr>
<td>Soil shear strength Cu</td>
<td>42</td>
</tr>
</tbody>
</table>
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

\[ n_0 = 1 + \frac{A_c}{A} \left[ 0.5 + f\left( I_s, \frac{A_c}{A} \right) \right] - 1 \]

\[ f\left( I_s, \frac{A_c}{A} \right) = \frac{1 - I_s^2}{1 - I_s - 2I_s^2} \frac{(1 - 2I_s)\left( 1 - \frac{A_c}{A} \right)}{1 - 2I_s + \frac{A_c}{A}} \]

- \( n_0 \): 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 - Correction for $E_c/E_s$
Priebe - Soil Stress $P_s$
Priebe - Column Stress $P_c$

The diagram shows the relationship between the stress ratio $P_c/P$ and the area ratio $A/A_c$ for different angles (45 deg, 42.5 deg, 40 deg, 37.5 deg, 35 deg). The curves indicate how the stress ratio changes with the area ratio for each specified angle.
### Priebe Example

**Pad footing example**

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</tr>
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</table>

- **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 ν**: 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
- **f(vAc/A) = f(νAc/A)**: 0.89 0.75
- **Pc/Pa**: 7.18 7.67
- **Pc**: 546.5 458.6 kPa
- **Ps**: 76.1 59.8 kPa
- **Basic improvement factor n0**: 1.97 2.51

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### Additional Data

<table>
<thead>
<tr>
<th>Soil</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

- **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(vAc/A)**: 0.95 1.09
- **Pc/Ps**: 7.03 6.70
- **Ps**: 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

\[ P_c = K_{pc}(K_s \cdot v' + 4c_u) \]

- \( P_c \): 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

Maximum horizontal pressure equal to hydrostatic
Ks = 1 conditions

Zone of fluidised soil around poker
Construction of Column in Sand

Maximum horizontal pressure due to vertical loading from poker but limited by passive earth pressure

\[ K_s = K_p \]

- Zone of fluidised soil around poker
- Re-penetration
- Lift height
Penetration into Clays

Maximum horizontal pressure equal to passive earth pressure or cavity expansion limit pressure

Weight of poker and pulldown used to penetrate cohesive soils
Construction of Column in Clay

Maximum horizontal pressure due to vertical loading from poker but limited by passive earth pressure or cavity expansion limit pressure.

Re-penetration

Lift height
Compaction of Stone Column

Column diameter $d$

$\frac{s_h}{n_s q_b d/(L-x)}$

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