Lecture 9

NPTEL Course

GROUND IMPROVEMENT

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Failure Mechanisms of Stone Columns suggested in IS code

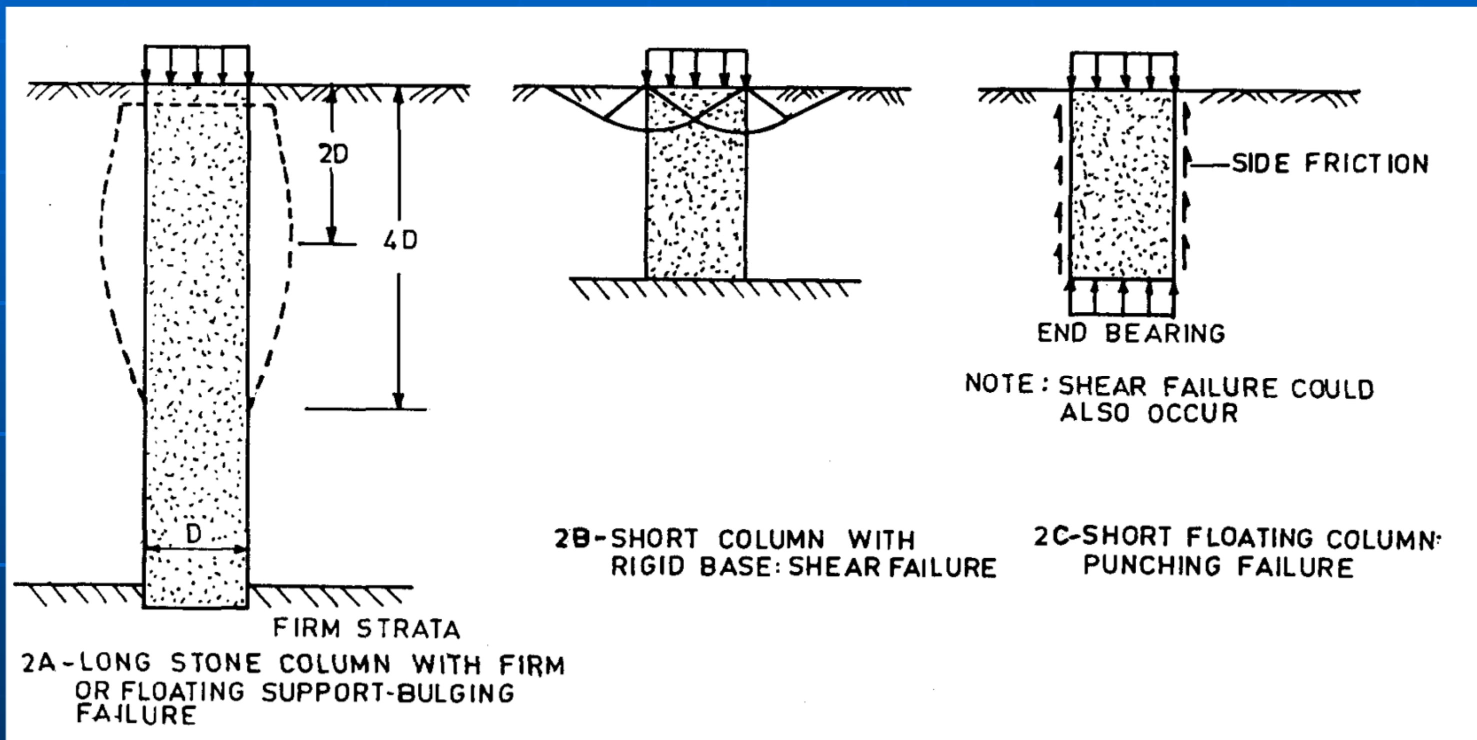


Fig1(a): Failure Mechanism of Single Stone Column in a Homogenous Soft Layer.

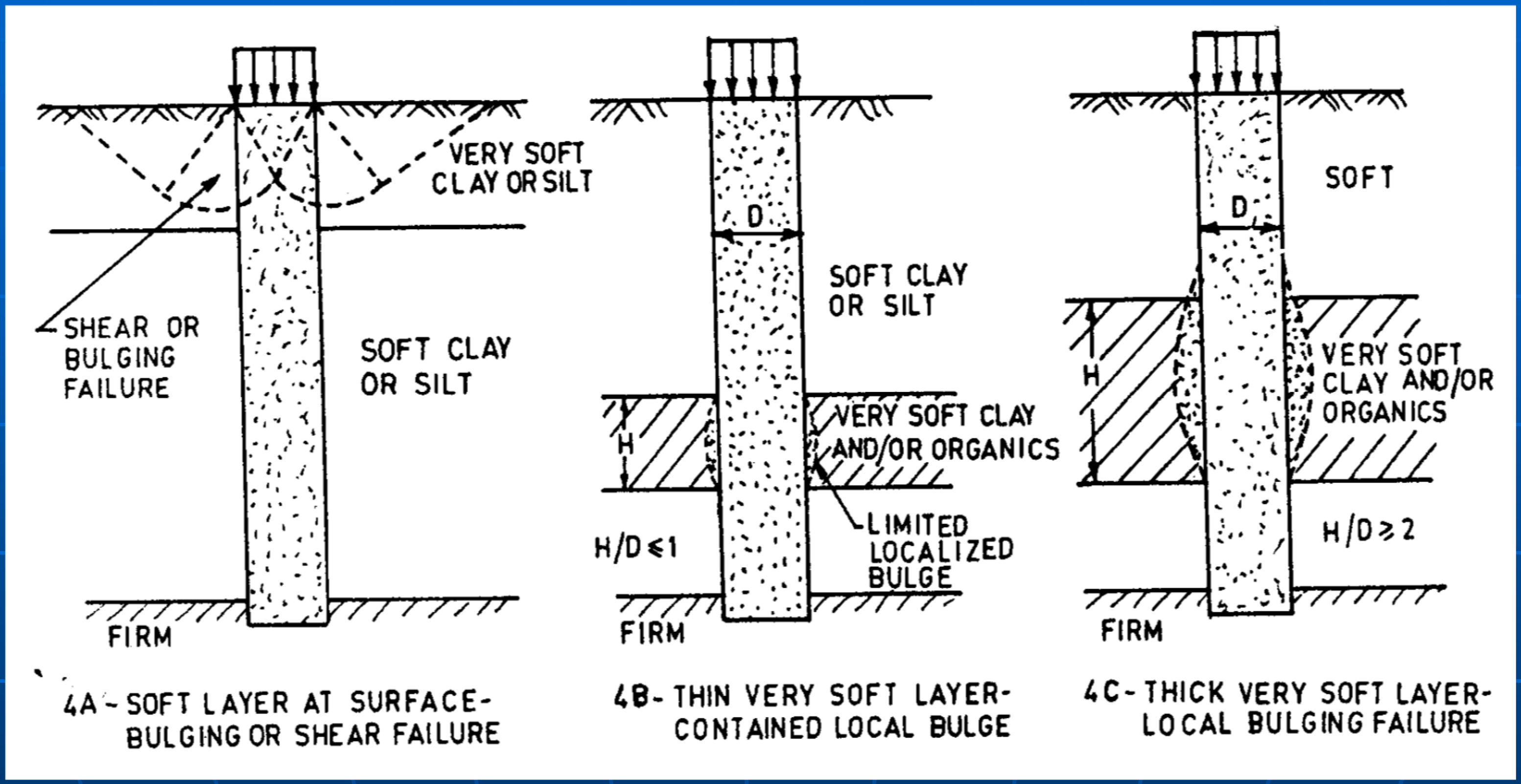


Fig1(b): Failure Mechanism of Single Stone Column in a Non-Homogenous Soft Layer.

Type of loading:

- In the case as shown in the fig1(b). where the loaded area is more than that of Stone columns experiences less bulging leading to ultimate load bearing capacity and reduced settlements since the load is carried by both soil and the stone columns.

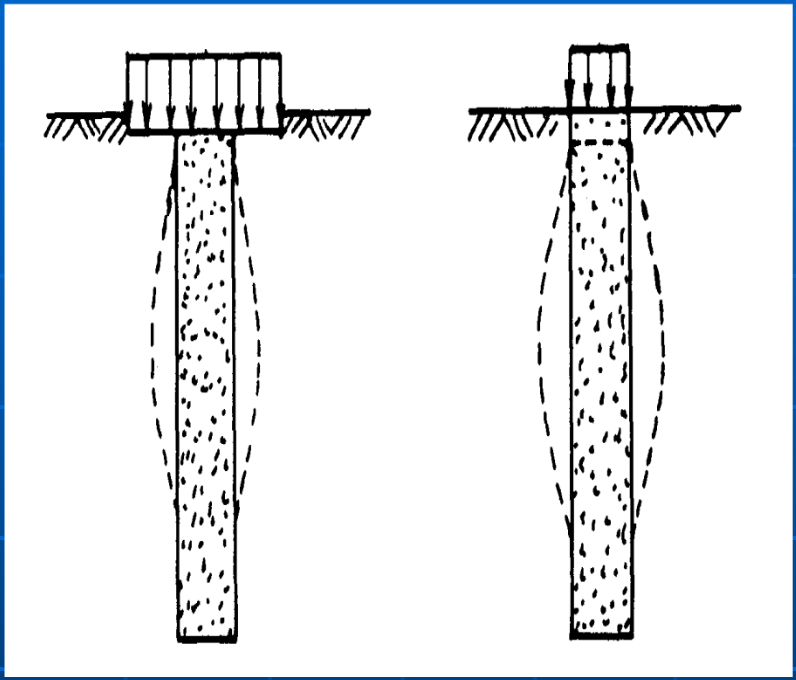


Fig1(c): Different types of loadings applied on Stone Columns.

Load Tests:

- From the Load test we can determine the ultimate load bearing capacity and settlement of single column with reasonable accuracy.
- A good experience with foundations on similar structures & calculations on the basis of principals of soil mechanics shall be made before final design.

Factor of Safety:

- The minimum Factor of safety against ultimate load capacity of column obtained from load test shall be **2.5**.

Installation Technique:

- The construction of stone columns involves creation of a hole In the ground which is later filled with granular fill / stone sand mixture and compacted to required strength.
- **Granular Blanket**: On the to top of stone columns a clean medium to coarse sand with 70-80% relative density is laid with a minimum thickness of 0.5m.
- This Layer should be exposed at its periphery to the atmosphere for easy dissipation of pore water pressure.

Field Tests:

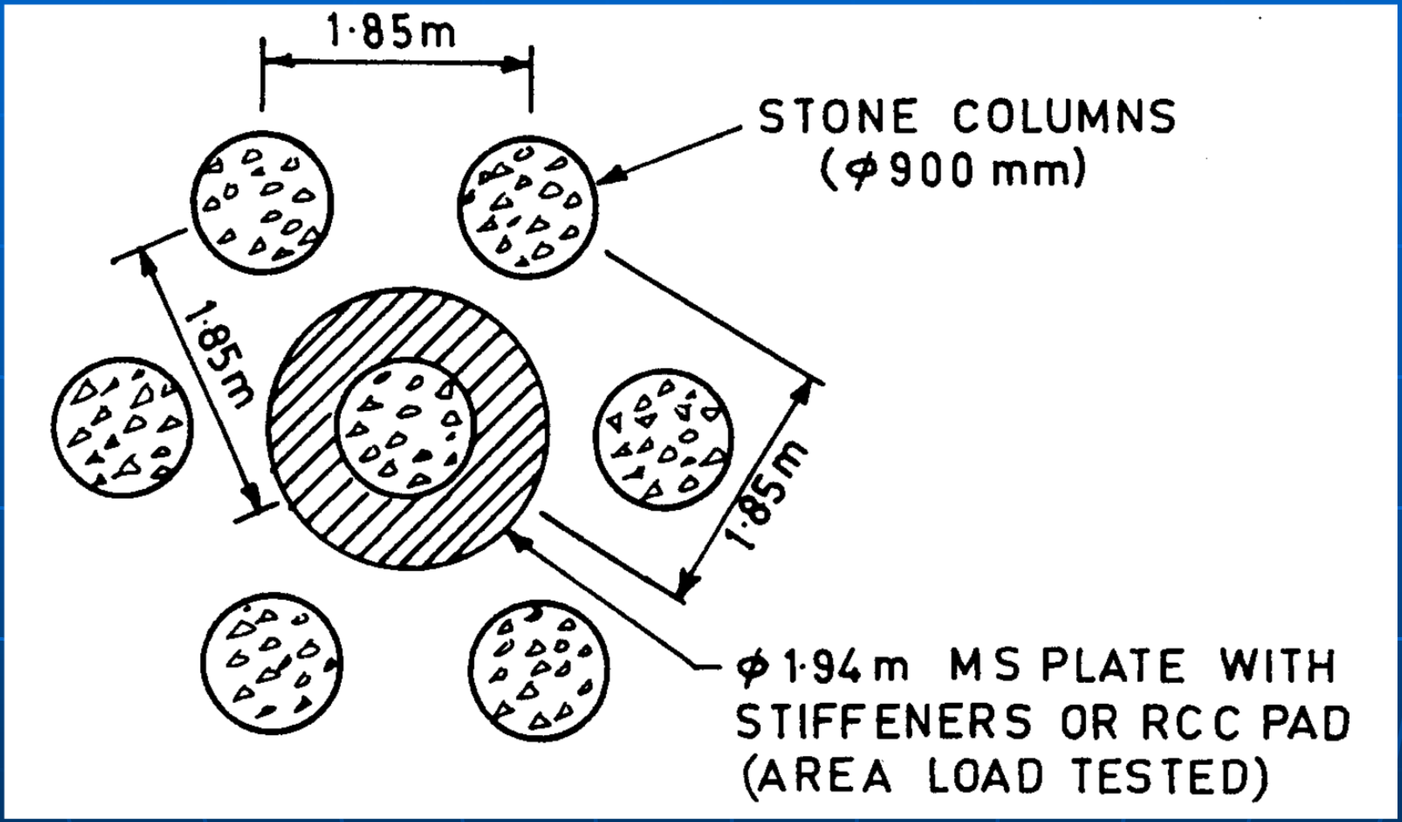


Fig1(d): Load test on single columns.

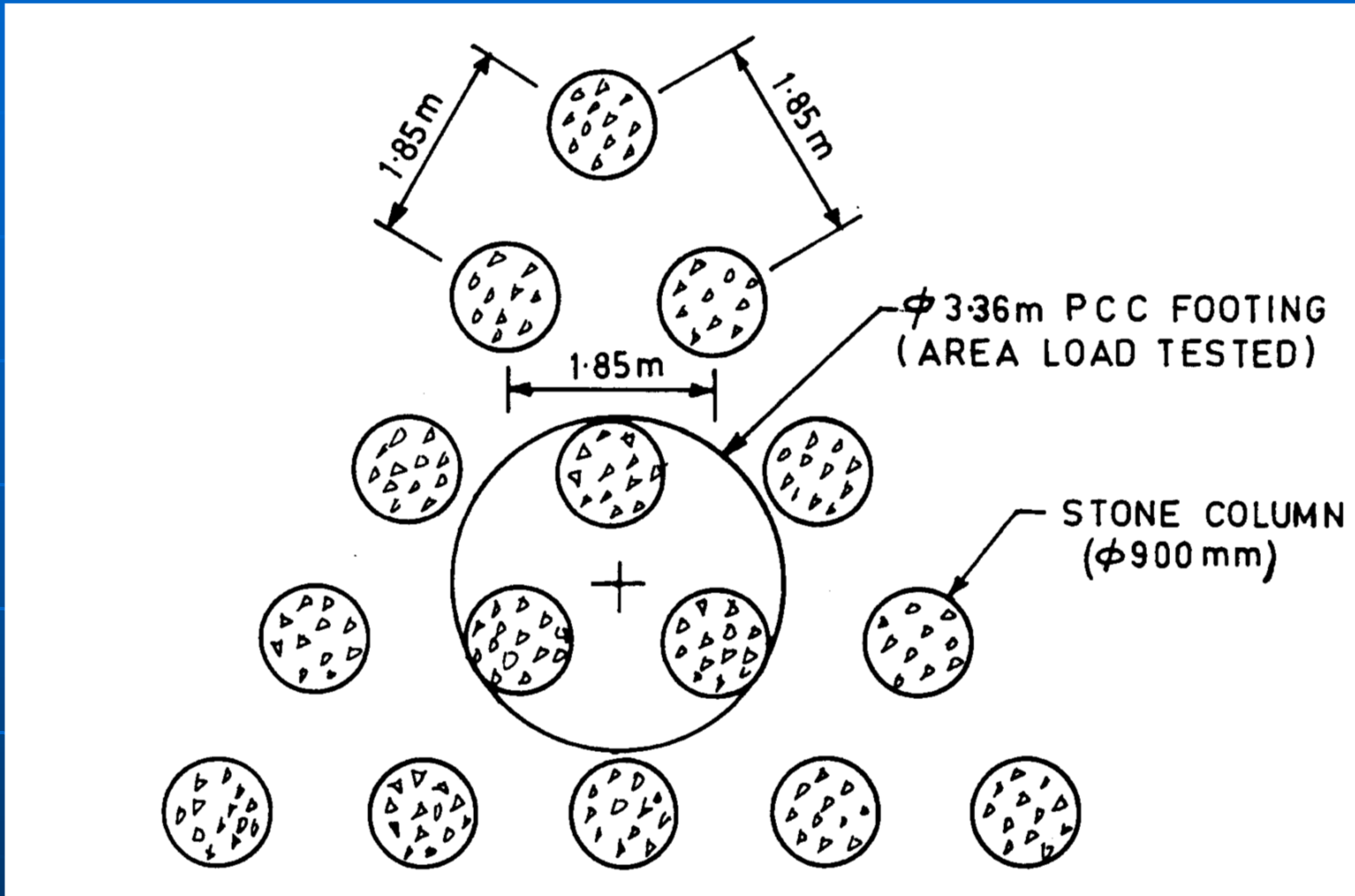


Fig1(d): Load test on Three columns(Group Test).

Design of Stone Columns Using Heinz J. Priebes Method

Contents

1. Introduction
2. Design of Stone Columns using Heinz J. Priebes method
3. Design example
4. Design using Stone C 3.3 Software

Introduction

- Vibro Replacement is an subsoil improvement method at which large-sized columns of coarse backfill material are installed in the soil by means of special depth vibrators.
- Vibro replacement improves non compactible cohesive soil by the installation of load bearing columns of well compacted, coarse grained backfill material contrary to vibro compaction used for cohesion less soils.
- The extent to which the density of compactible soil will be improved by vibro- compaction, depends not only on the parameters of the soil being difficult to determine, but also on the procedure adopted and the equipment provided.

Design of Stone Columns using Heinz J. Priebes method

Basic principle

Load distribution and lateral support from the stone column & surrounding stiffened ground on an area basis are considered to give an improvement factor. The improvement factor indicates increase in compression modulus and the extent to which the settlement is reduced by the column ground improvement.

The design method refers to the improving effect of stone columns in a soil which is otherwise unaltered in comparison to the initial state. i.e. the installation of stone columns densifies the soil between.

The following idealized conditions are assumed in the design:

- The column is based on a rigid layer
- The column material is uncompressible
- The bulk density of column and soil is neglected. Hence, the column can not fail in end bearing and any settlement of the load area results in a bulging of the column which remains constant all over its length.

Notations Used

A	grid area	p	area load resp. foundation pressure
b	foundation width	s	settlement
c	cohesion	W	weight
d	improvement depth	α	reduction faktor in earthquake design
d_{Gr}	depth of ground failure	γ	unit weight
D	constrained modulus	η	safety against ground failure
f_d	depth factor	μ	Poisson´s ratio
K	coefficient of earth pressure	σ_{0f}	bearing capacity
m	proportional load on stone columns	φ	friction angle
n	improvement factor		

Used subscripts, dashes and apostrophes follow from the context. Generally, subscript C means column and S means soil. With the exception of K_0 as coefficient for earth pressure at rest (K_a for active earth pressure) subscript 0 means a basic respectively an initial value.

Determination of the Basic Improvement Factor, n_o

In a first step, the Basic improvement factor is calculated by using the following equation, n_o . A is the unit cell area and A_c is the area of column.

$$n_0 = 1 + \frac{A_C}{A} \cdot \left[\frac{1/2 + f(\mu_S, A_C/A)}{K_{aC} \cdot f(\mu_S, A_C/A)} - 1 \right]$$

$$f(\mu_S, A_C/A) = \frac{(1-\mu_S)\cdot(1-A_C/A)}{1-2\mu_S + A_C/A}$$

$$K_{aC} = \tan^2(45° - \varphi_C/2)$$

A poisson's ratio of μ_S **= 1/3** which is adequate for the state of final settlement in most cases, leads to a simple expression.

$$n_0 = 1 + \frac{A_C}{A} \cdot \left[\frac{5 - A_C/A}{4 \cdot K_{aC} \cdot (1 - A_C/A)} - 1 \right]$$

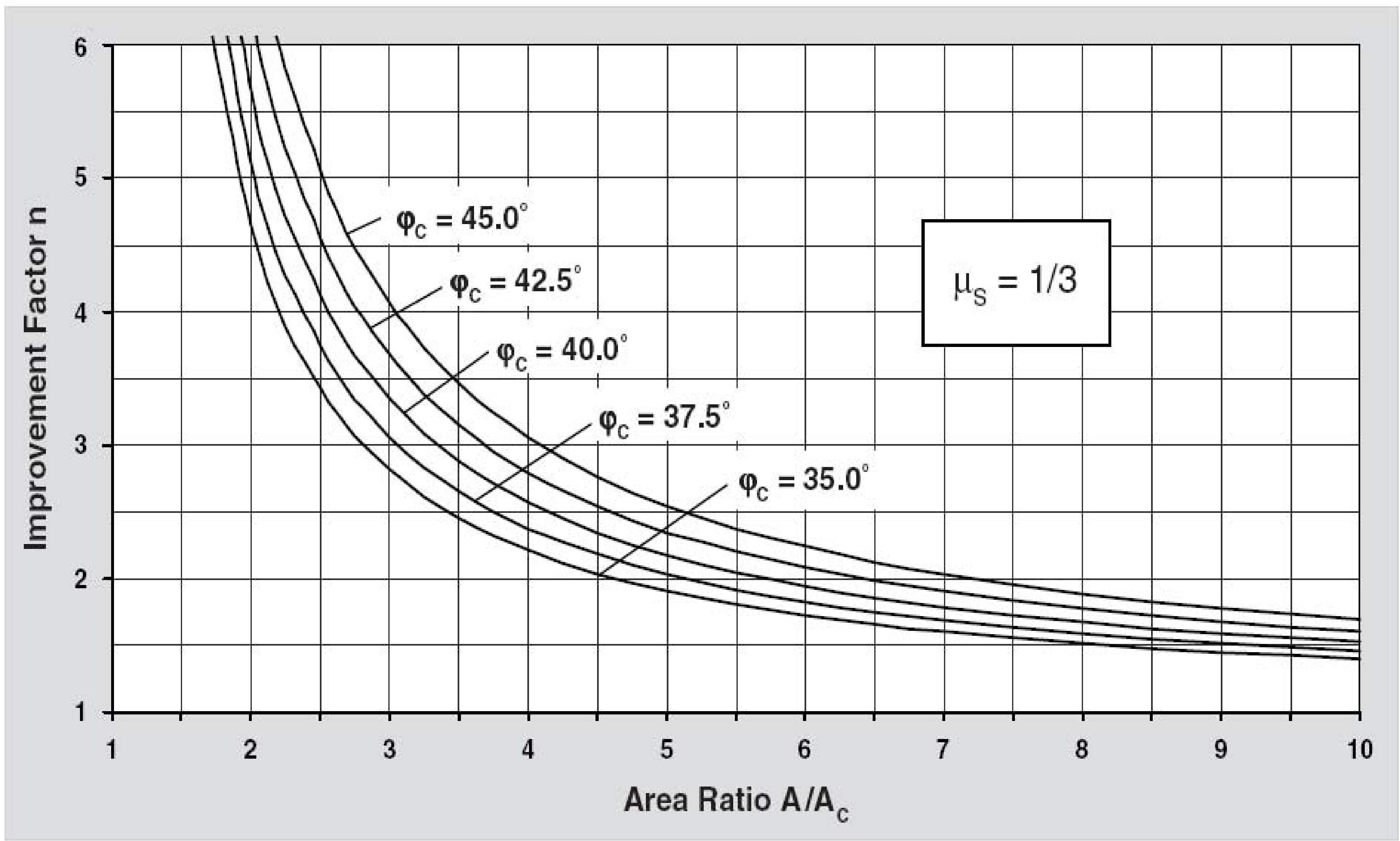


Fig1(a): Relation between the improvement factor n_0, the reciprocal area ratio A/A_C and the friction angle of the backfill material, ϕ_c.

Consideration of Column Compressibility

The compressibility of the column material can be considered in using a reduced improvement factor n_1 which results from the formula developed for the basic improvement factor, n_0 when the given reciprocal area ratio A/AC is increased by an additional amount of Δ(A/AC).The Reduced Improvement Factor is calculated by using the following equation, n_1

$$n_1 = 1 + \frac{\overline{A_C}}{A} \cdot \left[\frac{1/2 + f(\mu_S, \overline{A_C/A})}{K_{aC} \cdot f(\mu_S, \overline{A_C/A})} - 1 \right]$$

$$\frac{\overline{A_C}}{A} = \frac{1}{A/A_C + \Delta(A/A_C)}$$

$$\Delta(A/A_C) = \frac{1}{(A_C/A)_1} - 1$$

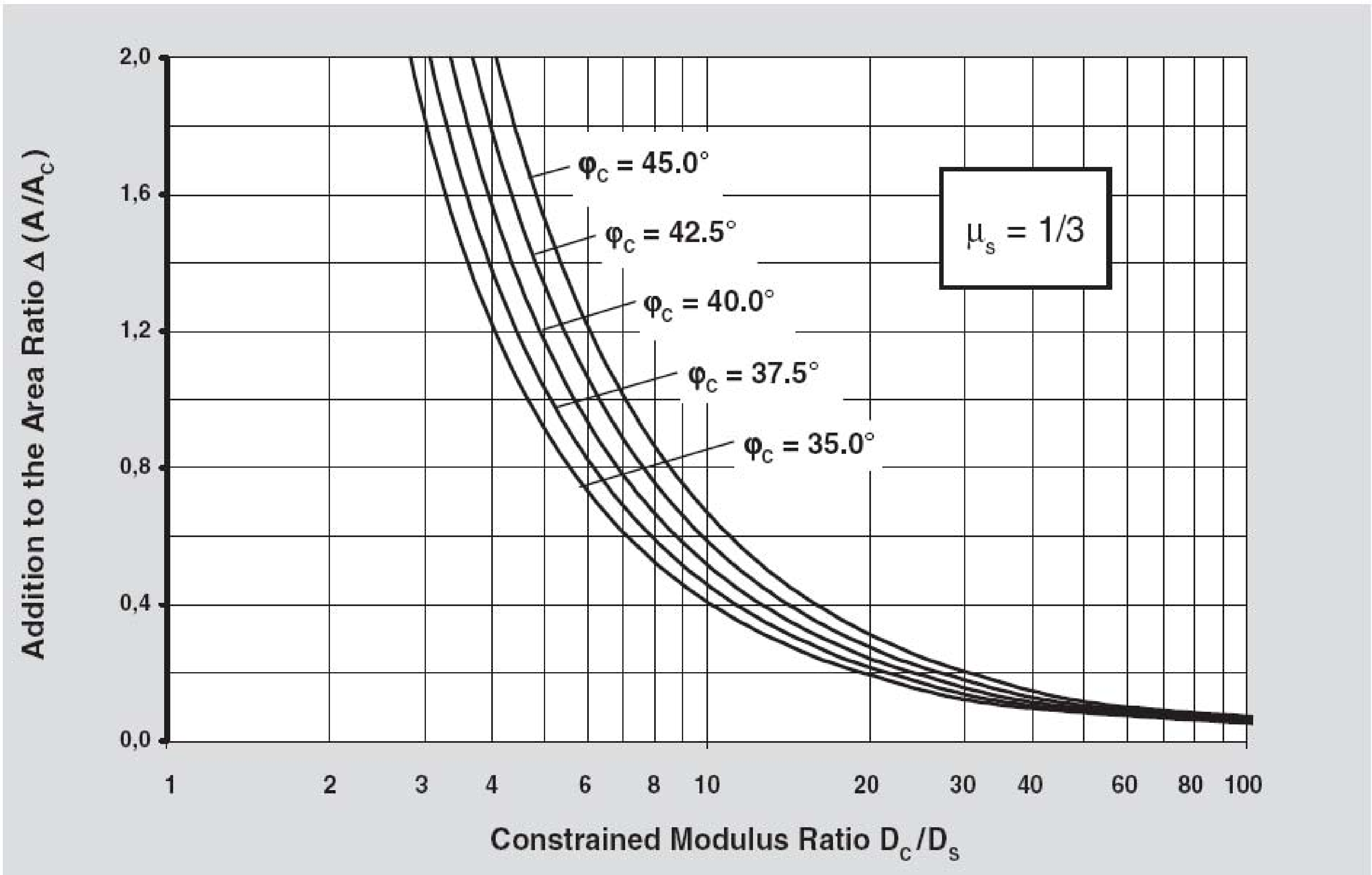


Fig1(b): Variation of Additional amount on the area ratio Δ(A/AC) with the ratio of the constrained moduli D_C/D_S.

Consideration of the Overburden

1)The neglect of the bulk densities of columns and soil means that the initial pressure difference between the columns and the soil which creates bulging, depends solely on the distribution of the foundation load p on columns and soil, and that it is constant all over the column length.

2)The consideration of external loads the weights of the columns WC and of the soil WS which possibly exceed the external loads considerably decreases the pr. difference and the bulging is reduced.

3)The pressure difference is a linear parameter in the derivations of the improvement factor, the ratio of the initial pressure difference and the one depending on depth- expressed as depth factor fd - delivers a value by which the improvement factor n1 increases to the final improvement factor $\mathbf{n_2 = fd \times n_1}$.

The depth factor fd can be determined from the following equations:

$$f_d = \frac{1}{1 + \frac{K_{0C} - W_S/W_C}{K_{0C}} \cdot \frac{W_C}{p_C}}$$

$$p_C = \frac{p}{\frac{\overline{A_C}}{A} + \frac{1 - \overline{A_C/A}}{p_C/p_S}}$$

$$\frac{p_C}{p_S} = \frac{1/2 + f(\mu_S, \overline{A_C/A})}{K_{aC} \cdot f(\mu_S, \overline{A_C/A})}$$

$$W_C = \Sigma(\gamma_C \cdot \Delta d), \qquad W_S = \Sigma(\gamma_S \cdot \Delta d)$$

$$K_{oC} = 1 - \sin \varphi_C$$

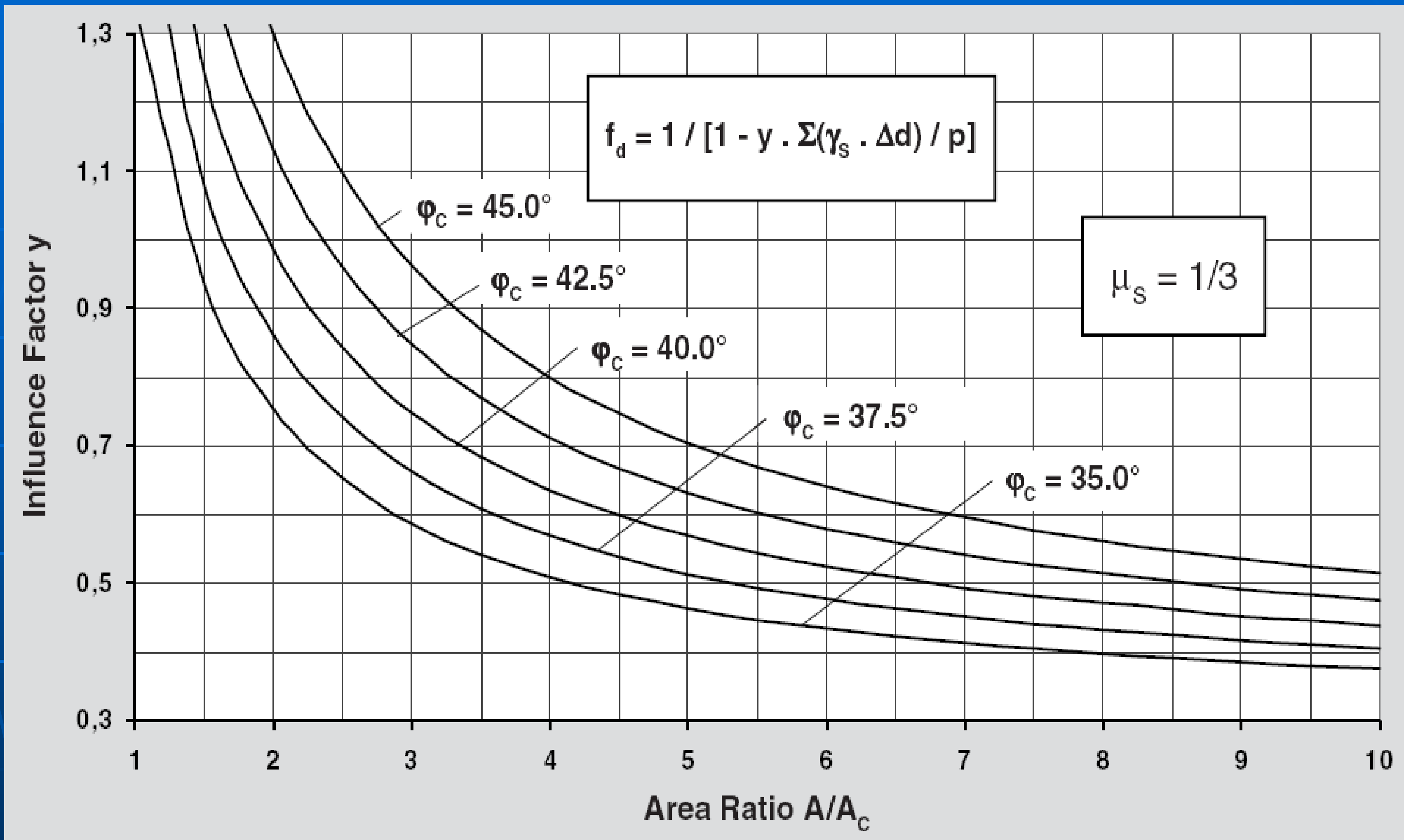


Fig 1(c): Variation of Influence factor, y for different values of friction angles.

Shear Values of Improved Ground

- The shear resistance from friction of the composite system can be determined by using the following equation:

$$\tan\bar{\varphi} = m' \cdot \tan\varphi_C + (1 - m') \cdot \tan\varphi_S$$

$$m' = (n-1)/n$$

- The cohesion of the composite system depends on the proportional to the loads using the following equation.

$$c = (1 - \overline{A_C/A}) \cdot c_S$$

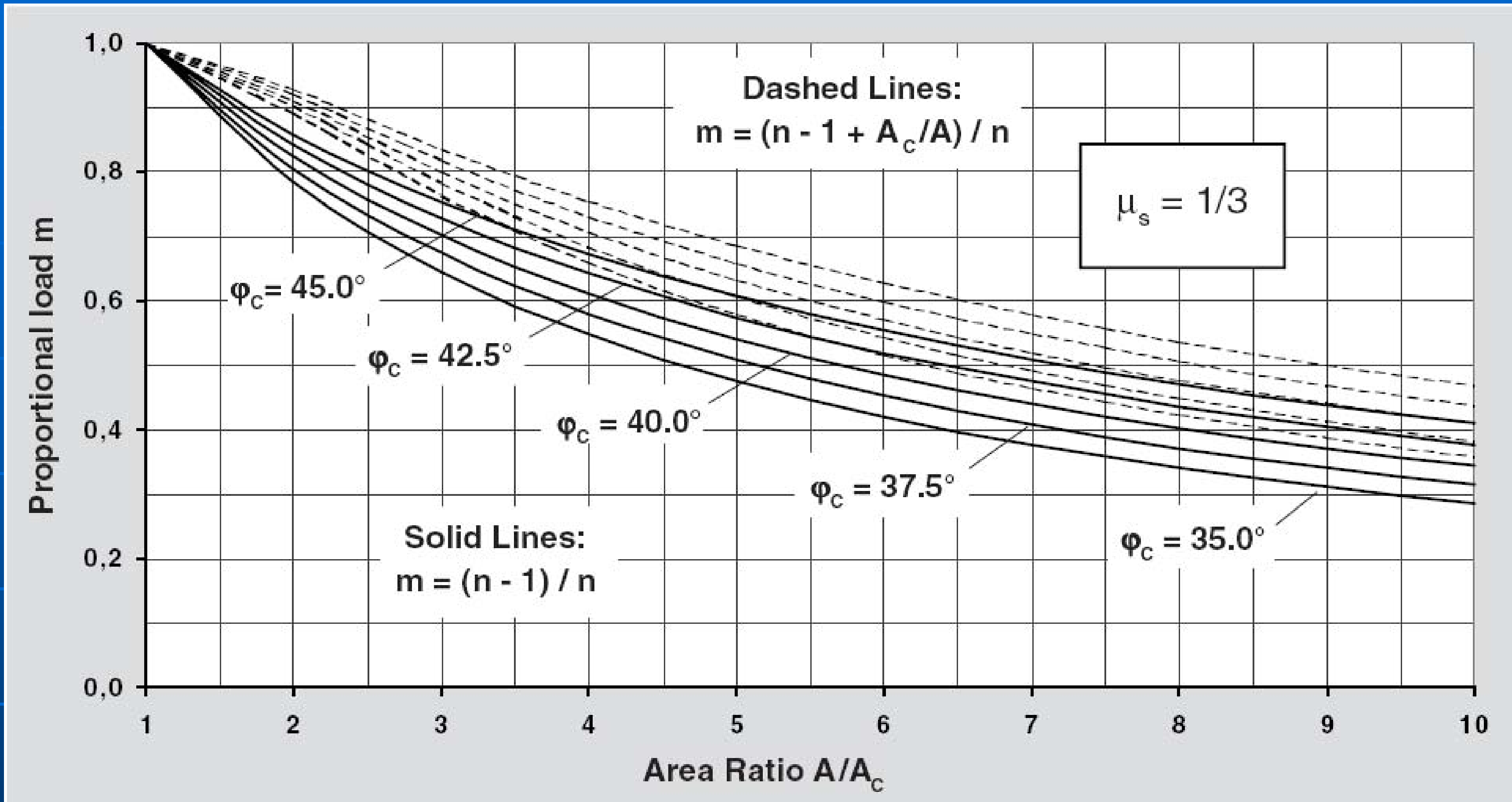


Fig1(d): Proportional Load on Stone Columns for different values of friction angles.

Settlement of improved Ground

- The design ensues from the performance of an unlimited column grid below an unlimited load area. The total settlement which results for this case at homogeneous conditions, is readily to determine on the basis of the foregoing description with n2 as an average value over the depth d is given by the following equation:

$$s_\infty = p \cdot \frac{d}{D_S \cdot n_2}$$

- The settlement of the ground with out improvement is 25.1cm which is more than that of settlement with improvement of 5.1cm.

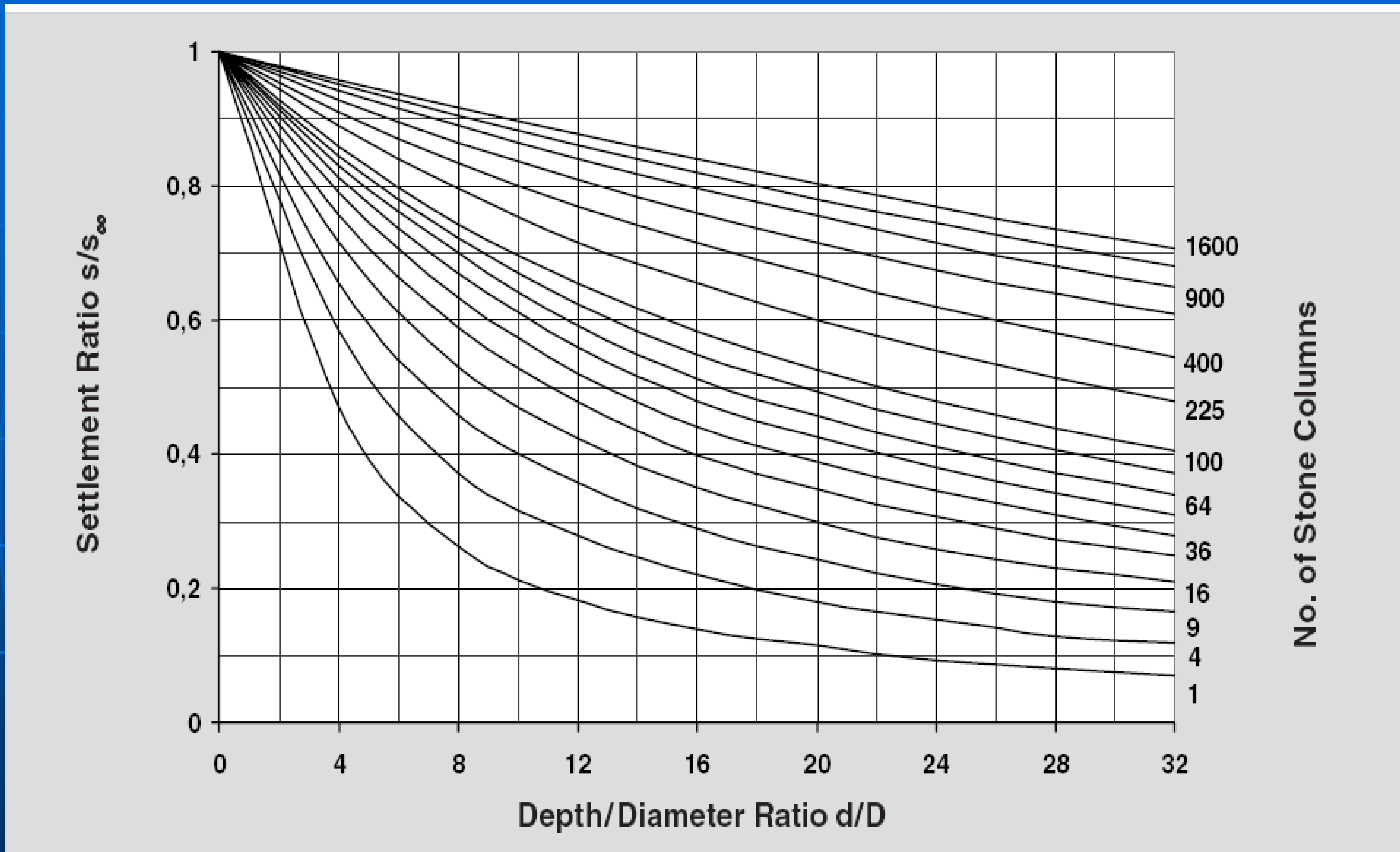


Fig1(e): Variation of settlement ratio with d/D ratio of Single Footing

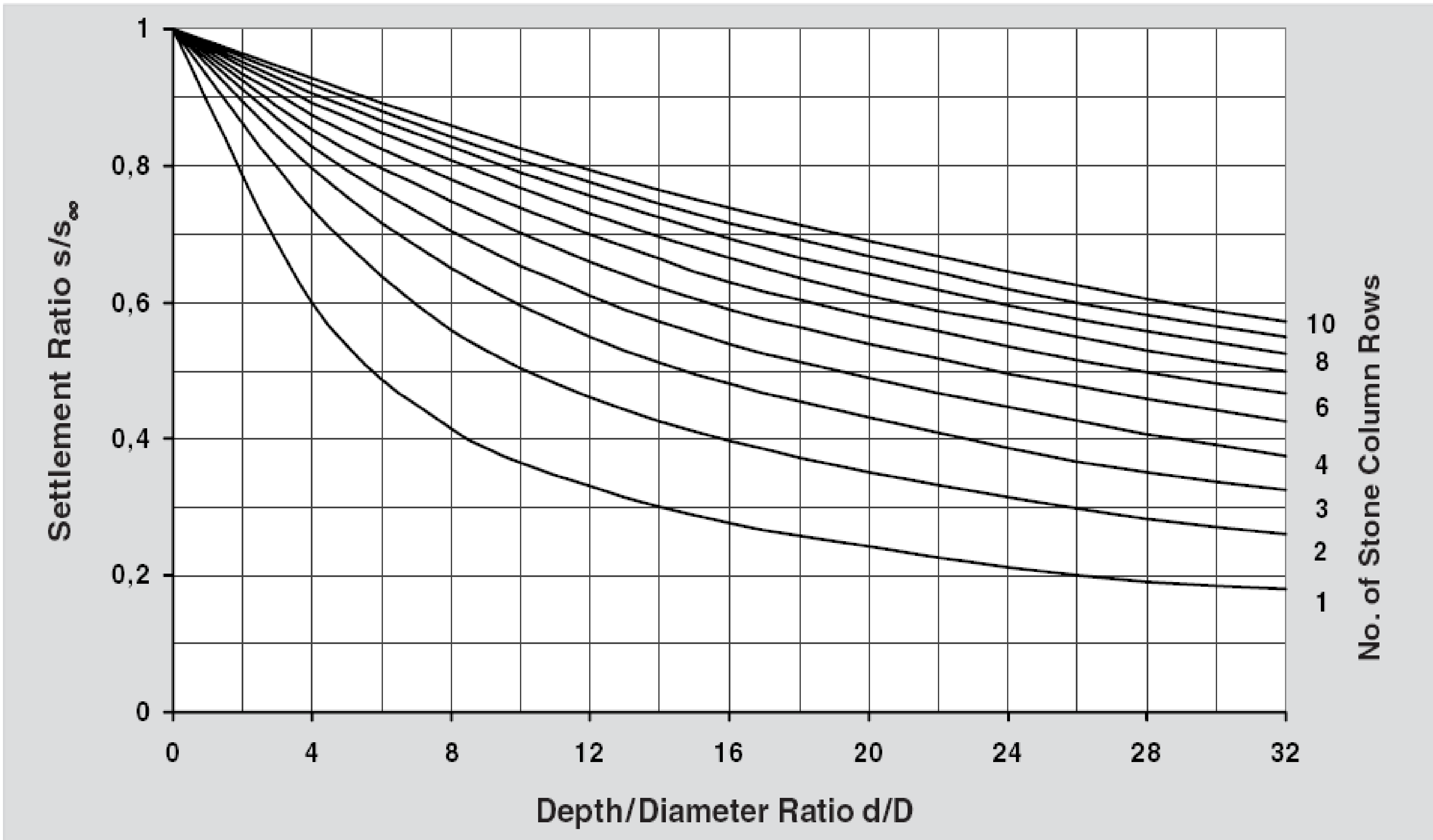


Fig1(f): Variation of settlement ratio with d/D ratio of Strip Footing

Bearing capacity of improved ground

Safety factor against bearing capacity of the soil can be determined using using the following equations:

$$\overline{\sigma_{0f}} = (c_S \cdot N_c \cdot \nu_c + q \cdot N_d \cdot \nu_d + \gamma_S \cdot \bar{b} \cdot N_b \cdot \nu_b) \cdot \bar{b}/b$$

Factor of Safety Against Bearing capacity= σ_{0f}/P

Design Example

- Design stone columns for an embankment with the following properties:

Top width of embankment= 5.0m with 1:1 slope on both sides. Surcharge on embankment=20kPa; Unit Wt. of embankment fill= 20KN/m^3 with depth of stone column= 6.0m. Given friction angle of column material= 40degrees; Cohesion=20kpa; Friction angle of soil= 0 degrees; μs=1/3; Column diameter=0.75m; Unit Wt. of Soil=16 KN/m^3.

Step1) Basic Improvement factor(no) given by:

$$n_0 = 1 + \frac{A_C}{A} \cdot \left[\frac{1/2 + f(\mu_S, A_C/A)}{K_{aC} \cdot f(\mu_S, A_C/A)} - 1 \right]$$

$$f(\mu_S, A_C/A) = \frac{(1-\mu_S)\cdot(1-A_C/A)}{1-2\mu_S + A_C/A}$$

$$K_{aC} = \tan^2(45° - \varphi_C/2)$$

K_{ac}= $Tan^2(45-\varphi_c/2)$= 0.217

Area of Column, Ac= 0.785*0.75^2 =0.441

Area of unit Cell, A= 1.5*1.5= 2.25

μ_s=0.33

By substituting the above values in no, we get basic improvement factor as,

n_o= 2.30

Step2) Determine Reduced improvement factor(n_1)

The compressibility of the column material can be considered in using a reduced improvement factor n1 which results from the formula developed for the basic improvement factor n0 when the given reciprocal area ratio A/A_C is increased by an additional amount of $\Delta(A/A_C)$.

$$n_1 = 1 + \frac{\overline{A_C}}{A} \cdot \left[\frac{1/2 + f(\mu_S, \overline{A_C/A})}{K_{aC} \cdot f(\mu_S, \overline{A_C/A})} - 1 \right]$$

$$\frac{\overline{A_C}}{A} = \frac{1}{A/A_C + \Delta(A/A_C)}$$

$$\Delta(A/A_C) = \frac{1}{(A_C/A)_1} - 1$$

$$\left(\frac{A_C}{A}\right)_1 = -\frac{4 \cdot K_{aC} \cdot (n_0 - 2) + 5}{2 \cdot (4 \cdot K_{aC} - 1)} \pm \frac{1}{2} \cdot \sqrt{\left[\frac{4 \cdot K_{aC} \cdot (n_0 - 2) + 5}{4 \cdot K_{aC} - 1}\right]^2 + \frac{16 \cdot K_{aC} \cdot (n_0 - 1)}{4 \cdot K_{aC} - 1}}$$

Assuming constrained modulus Ratio, $D_c/D_s=100$, we get $\Delta A/A_c=0.05$ and substituting, we get.

Reduced Improvement factor, $n_1=2.28$

Step3) The depth factor fd can be determined from the following equations:

$$f_d = \frac{1}{1 + \frac{K_{0C} - W_S/W_C}{K_{0C}} \cdot \frac{W_C}{p_C}}$$

$$p_C = \frac{p}{\frac{\overline{A_C}}{A} + \frac{1 - \overline{A_C}/A}{p_C/p_S}}$$

$$\frac{p_C}{p_S} = \frac{1/2 + f(\mu_S, \overline{A_C}/A)}{K_{aC} \cdot f(\mu_S, \overline{A_C}/A)}$$

$$W_C = \Sigma(\gamma_C \cdot \Delta d), \qquad W_S = \Sigma(\gamma_S \cdot \Delta d)$$

$$K_{oC} = 1 - \sin\varphi_C$$

$f_d = 2.01$.

f_d = Depth factor due to overburden.

n_2=improved factor (with overburden constraint)

$n_2 = f_d * n1$

$= 2.01 * 2.28$

$= 4.58$

Step4) Determine improved shear values

- The shear resistance from friction of the composite system can be determined by using

$$\tan \overline{\varphi} = m' \cdot \tan \varphi_C + (1 - m') \cdot \tan \varphi_S$$

m'=0.561;

$$Tan\overline{\varphi} = \left(2 * 0.578 * \tan 40 + \left(1 - 0.578\right) * Tan0\right)$$

$$\overline{\varphi} = 47 \deg rees$$

- The cohesion of the composite system depends on the proportional to the loads using the following equation.

$$c' = (1 - m') \cdot c_S$$

$$c' = (1 - 0.561) * 20$$

C′=8.44kPa

Step6) Determine the bearing capacity of the soil.

$$\sigma of = \left(c_s.N_s.V_s + q.N_d.V_d + \gamma_s.\bar{b}.N_b.V_b \right).\frac{\bar{b}}{b}$$

$$\sigma of = \left(20*5.14*1.0 + 60*1.0*1.0 + 16*15*0*1.0\right)$$

$$\sigma 0f = 104.22Kpa$$

Factor of safety against bearing capacity=104.226/60.0=1.73

Introduction to Stone C Software

Main Characteristics

- Performs design calculations according to the method described by Priebe.
- Supports both rectangular and triangular stone columns grid installation patterns.
- Different stone columns diameters in every subsoil layer.
- Foundation type can be rectangular or circular.
- Performs settlements calculation using the basic theory of elasticity and according to Steinbrenner both for the treated and untreated soil.
- Performs bearing capacity calculations according to the method described by Priebe.
- Generates an extensive report of the results.

Steps to be followed for designing stone columns using Stone C Software

Step1) Input Stone columns grid & Foundation properties.

Step2) Input Column material properties.

Step3) Input Soil data.

Step4) Load project.

Step5) Click view results for the output values in a pdf document.

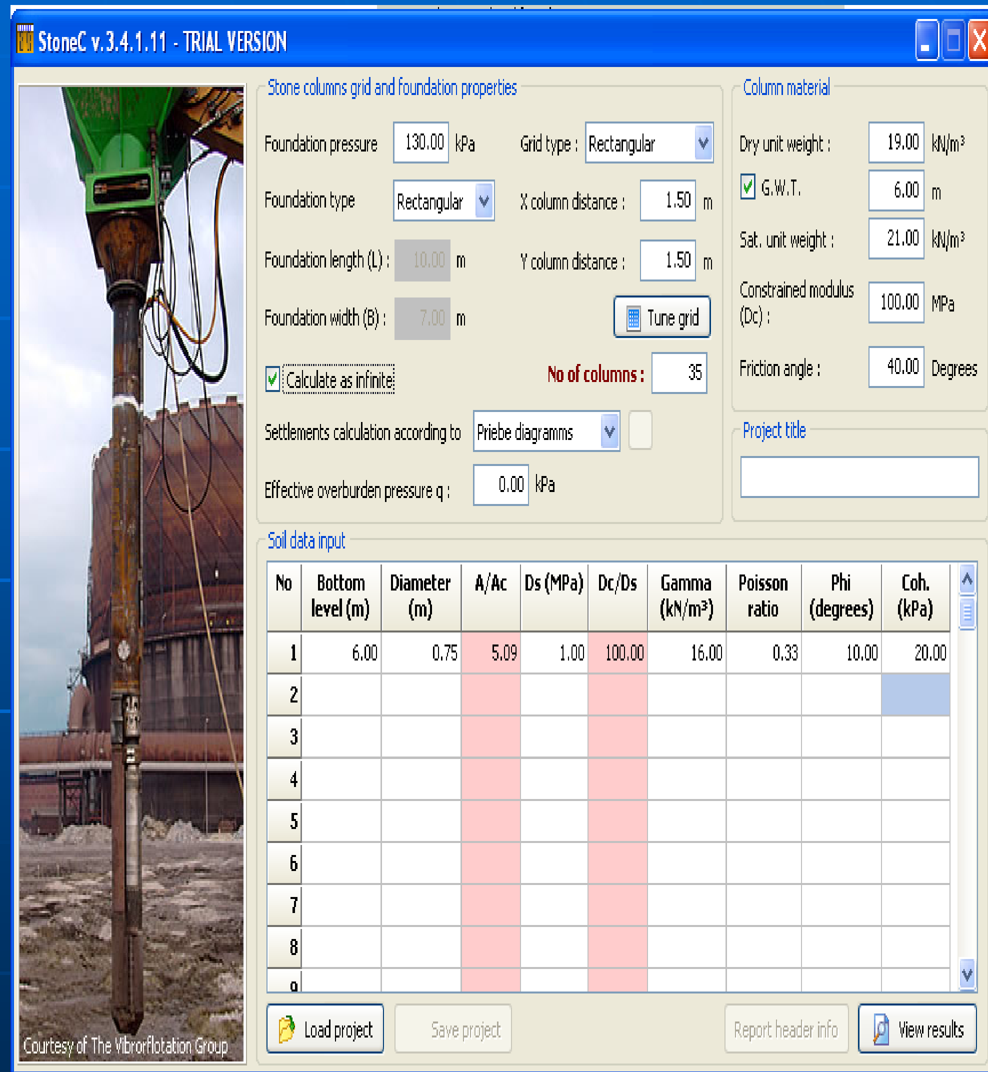
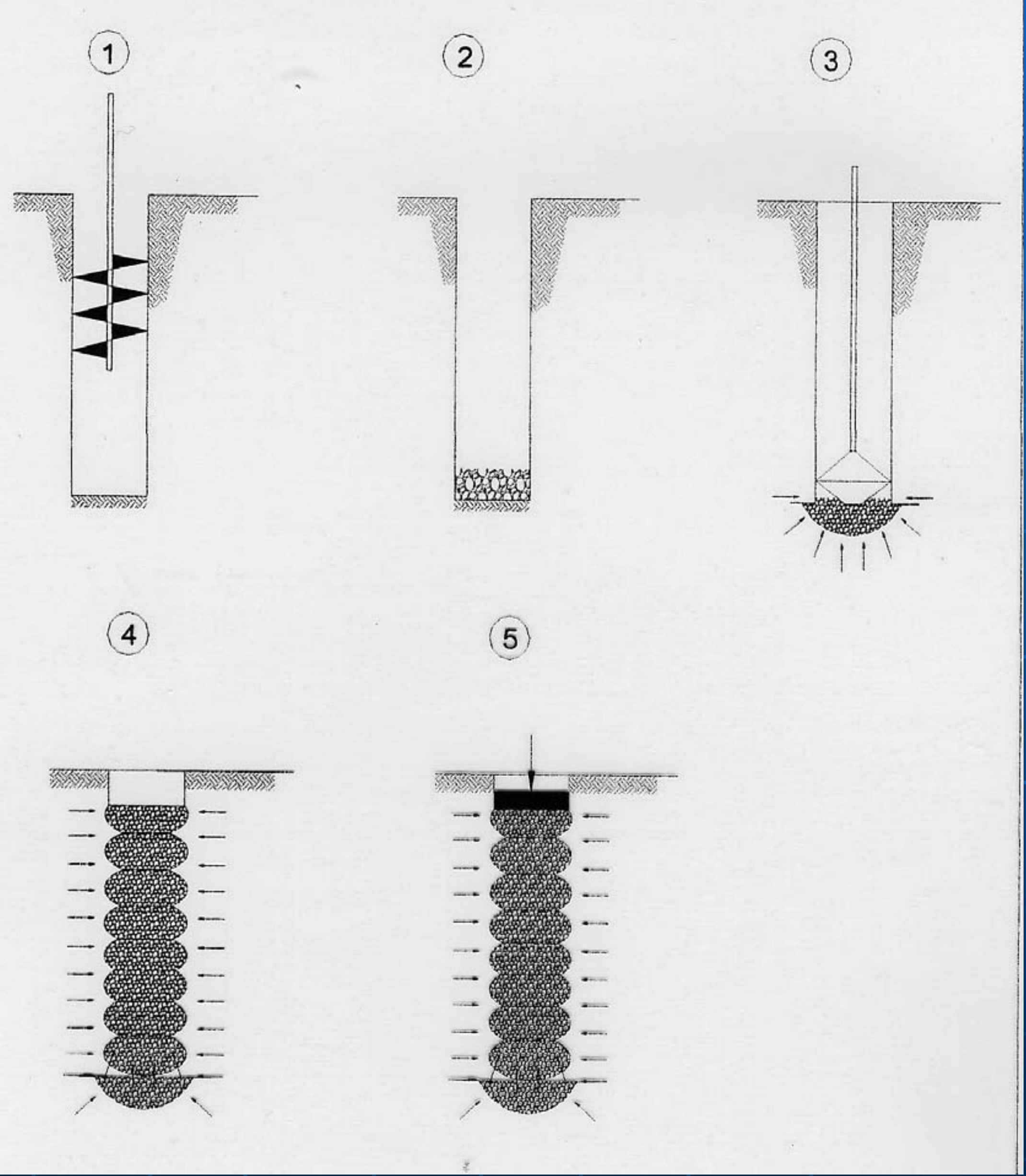


Fig: Stone C software.

Fig. Step Construction procedure of aggregate pier element



1. drill cavity using augers, install casing if cave-ins occur.
2. place crushed stone at the bottom of cavity.
3. ram bottom stone with beveled tamper to produce bulb.
4. densify crushed stone in layers of 30 cm with tamper.
5. preload top of rap element.

Aggregate piers versus stone columns

	stone columns	aggregate piers
Typical length	5-15m	2-8m
Typical spacing	4d	2d
Thickness of lifts	1.5-3 m	20-30 cm
Allowable foundation pressure	25-150 kPa	250-300 kPa
Typical length diameter ratio	5-30	2-4
Construction equipment	6 m probe mounted crane	backhoe with 4 m long tamper & aces

Limitations of aggregate piers

Disadvantages associated with aggregate piers can be categorized into two consisting of economic limitations and performance limitations.

The requirement of a drilled cavity, and the fact that almost all the soils requiring improvement with aggregate piers, being very soft and compressible, cavity collapse is an inevitable issue. To prevent this, temporary casing is placed, and advanced once the backfilling stage onsets. this slows down the application rate and increases the cost per element. Additionally where treatment zone depths are required to be greater than say 8 m, aggregate piers shall not be considered as a solution because they give best performance when used in compressible strata as a floating pile to depths up to 8 m.

Conclusions

- Vibro- compaction and vibro- replacement techniques have been used to a considerable extent in ground improvement projects
- They have been very cost effective in infrastructure projects.
- Drainage function of the stone columns has been very useful in mitigation of damages due to liquefaction.

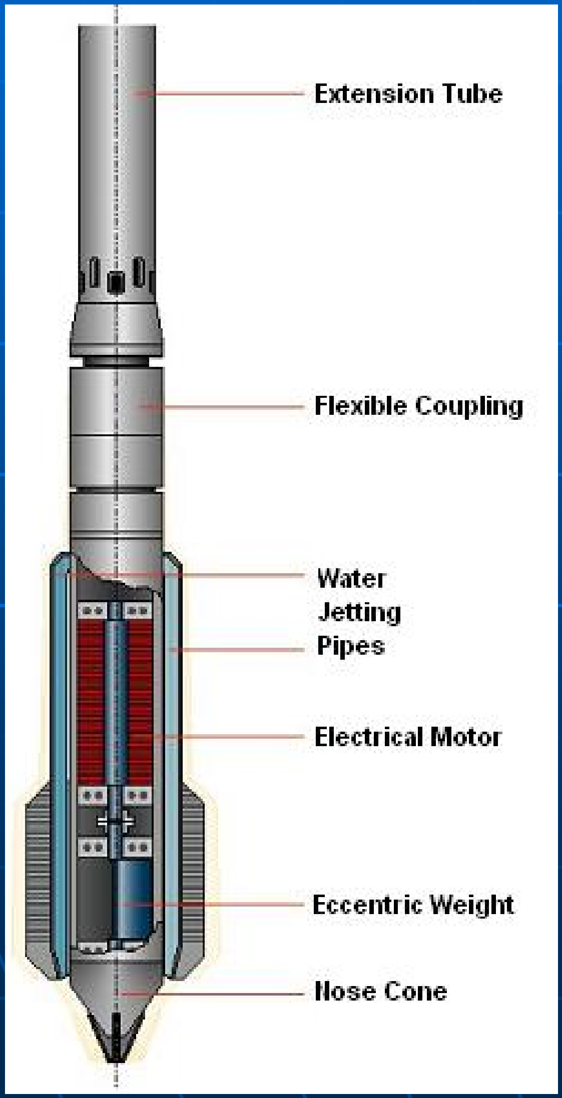
Vibro Replacement (Vibro Stone Column) Technique for Infrastructure Projects

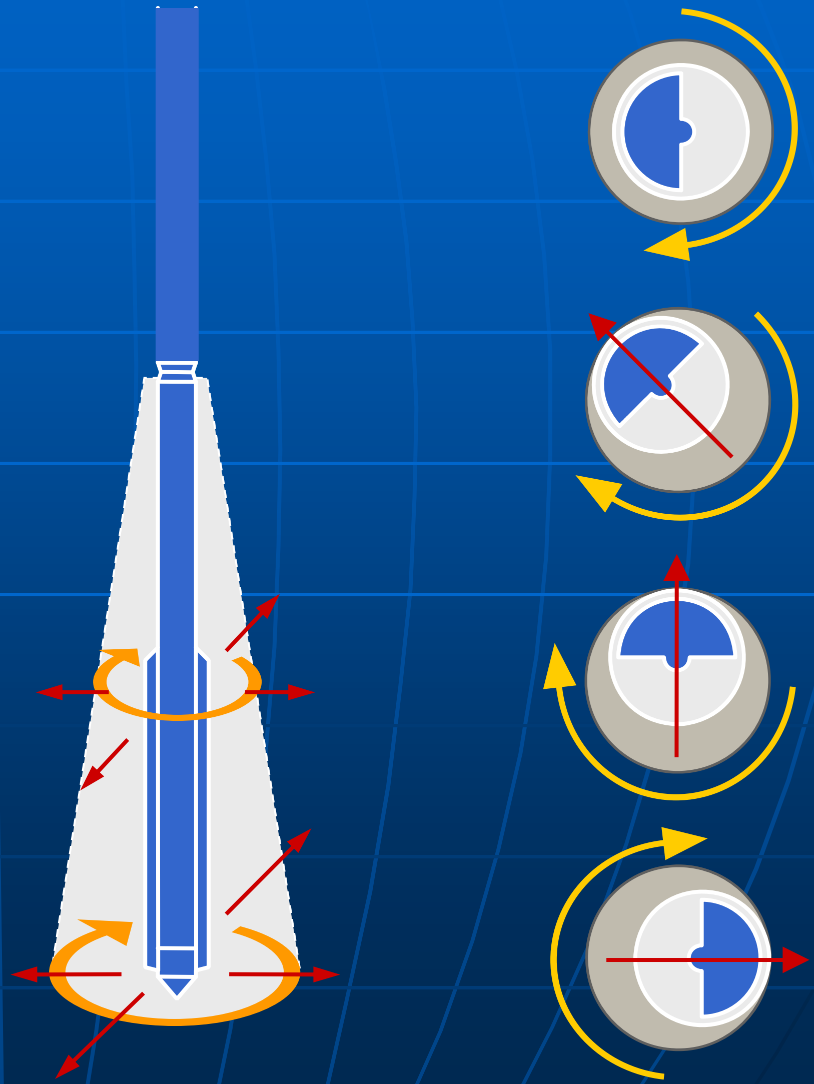
Contents

- Introduction – Vibro Replacement (Vibro Stone Columns)
- Specific Case Histories
  - Tank Farm
  - Port
  - Shipyard
  - Power Plants
  - Railways

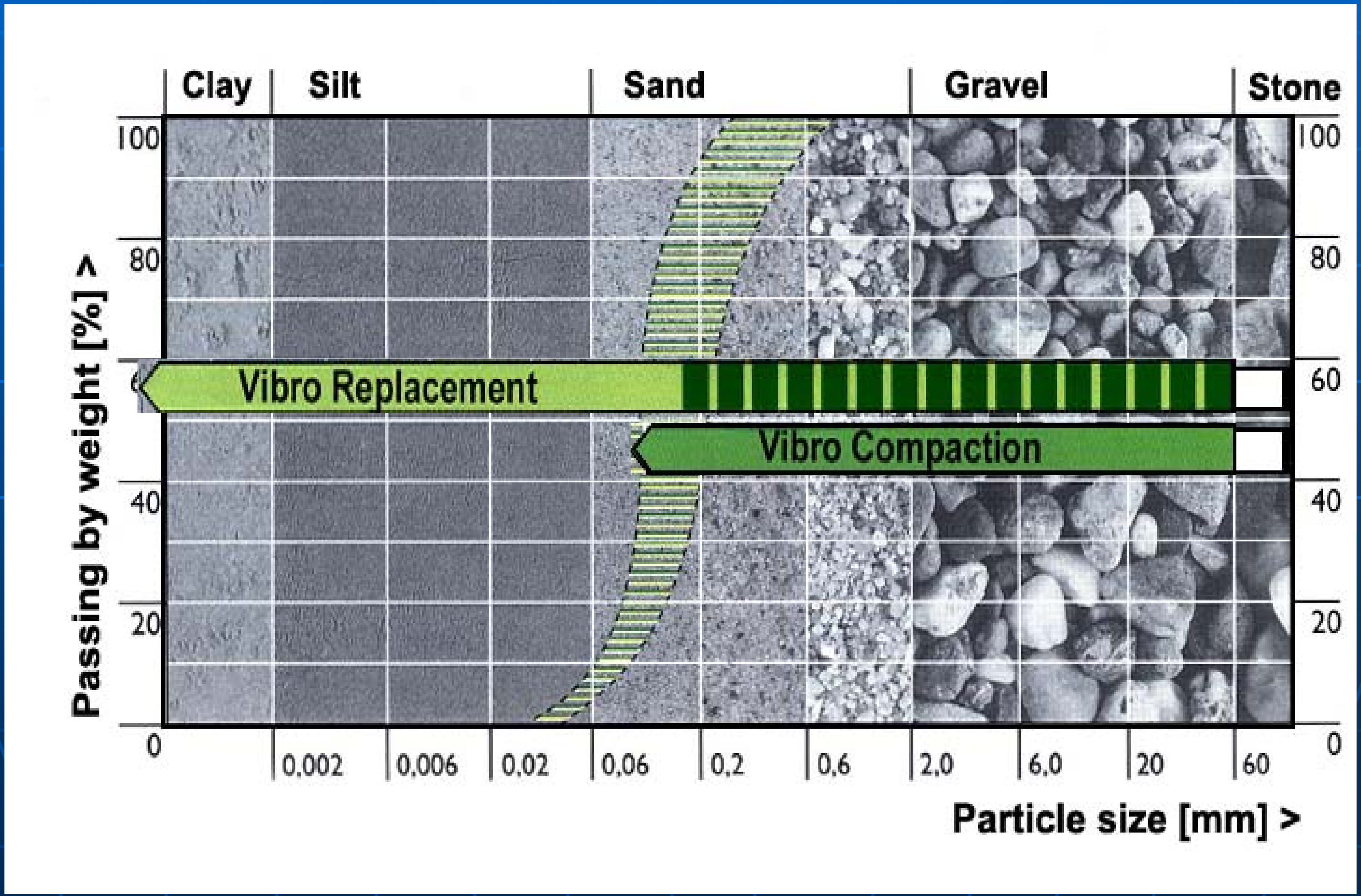
Introduction – Vibro Replacement (Vibro Stone Columns)

Depth Vibrators

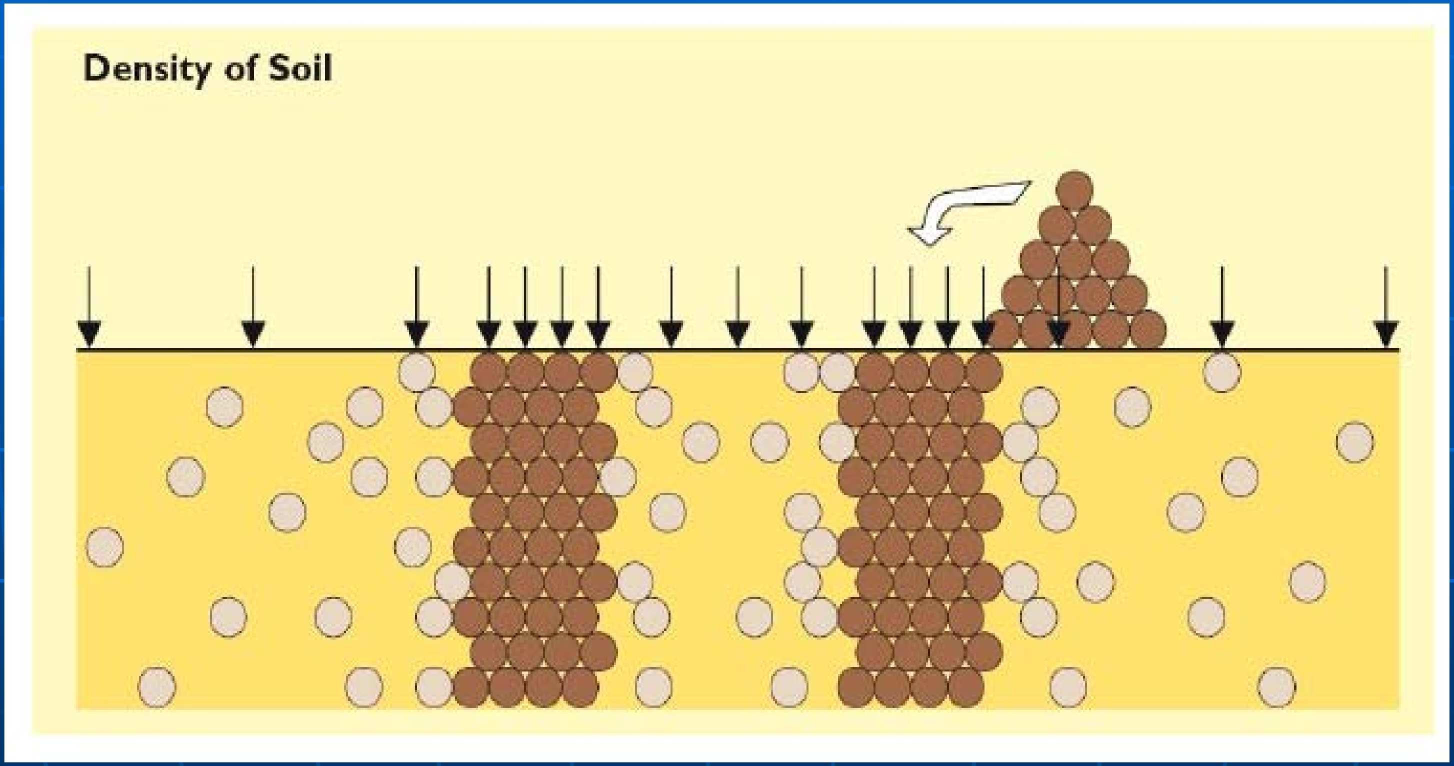




Applicable Soil Types

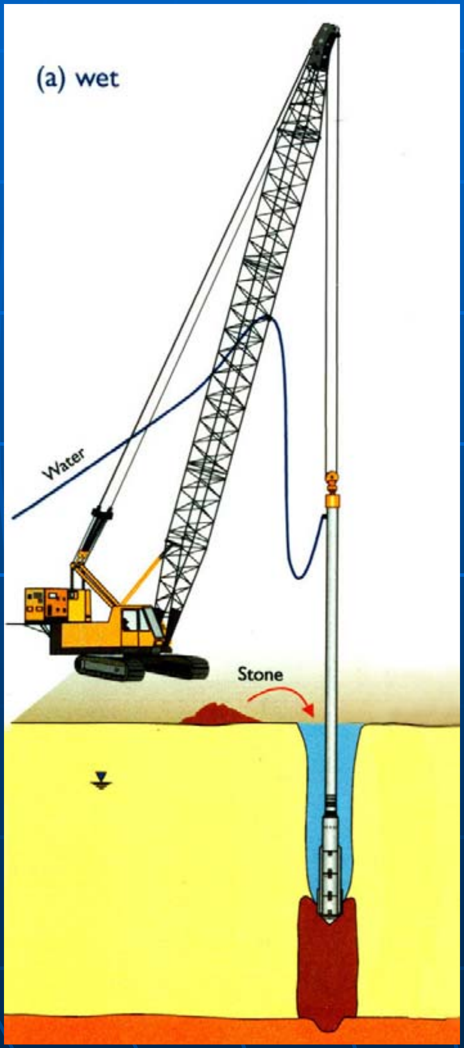


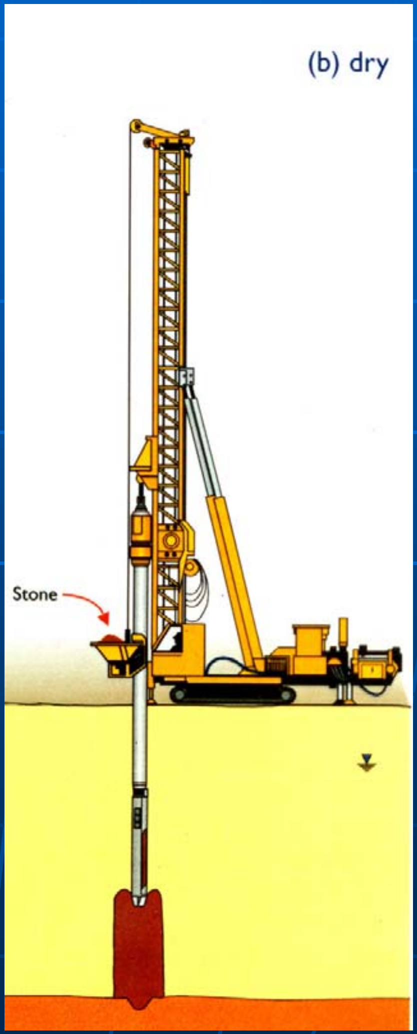
Vibro Replacement (Vibro Stone Columns)



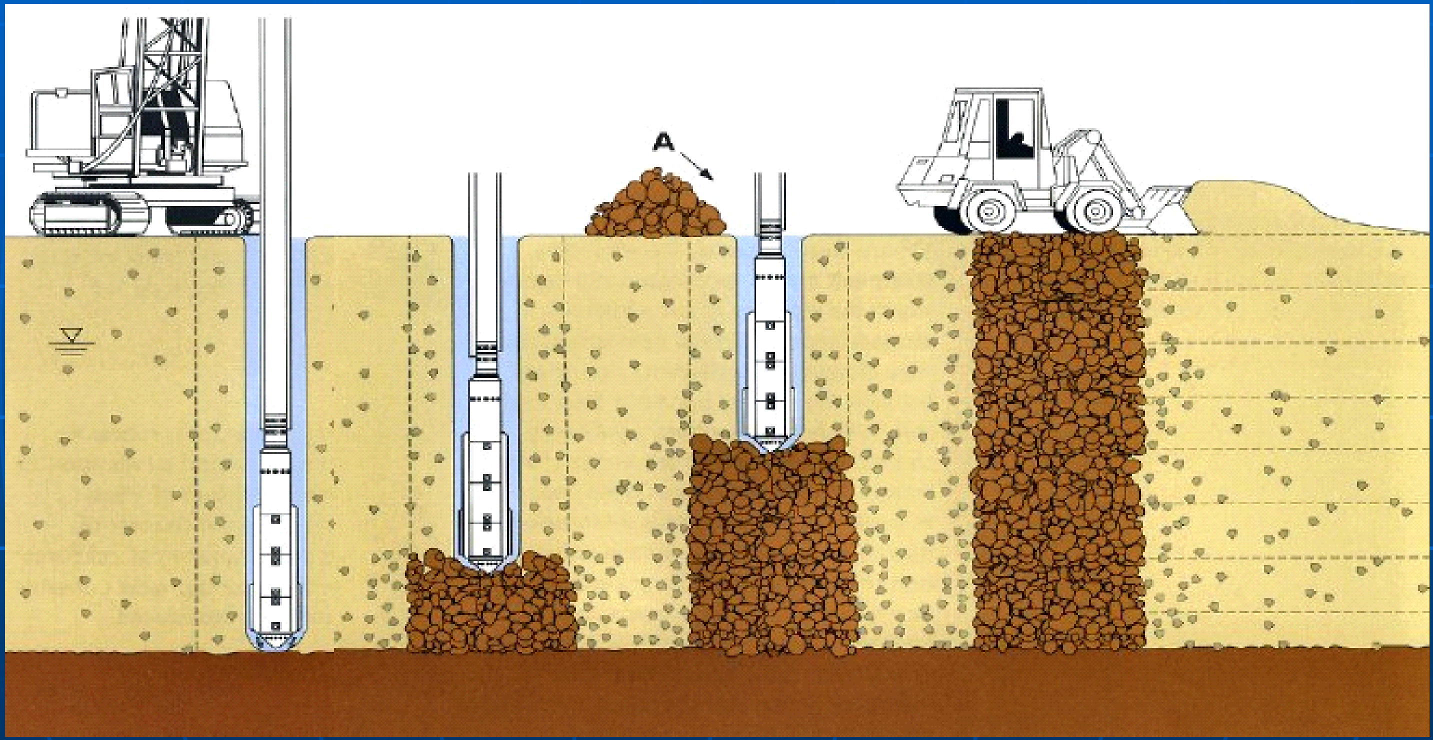
- Increase overall stiffness of compressible soils
- Increase shear strength
- Allow rapid consolidation by providing radial drainage

Vibro Stone Columns (Wet & Dry Methods)



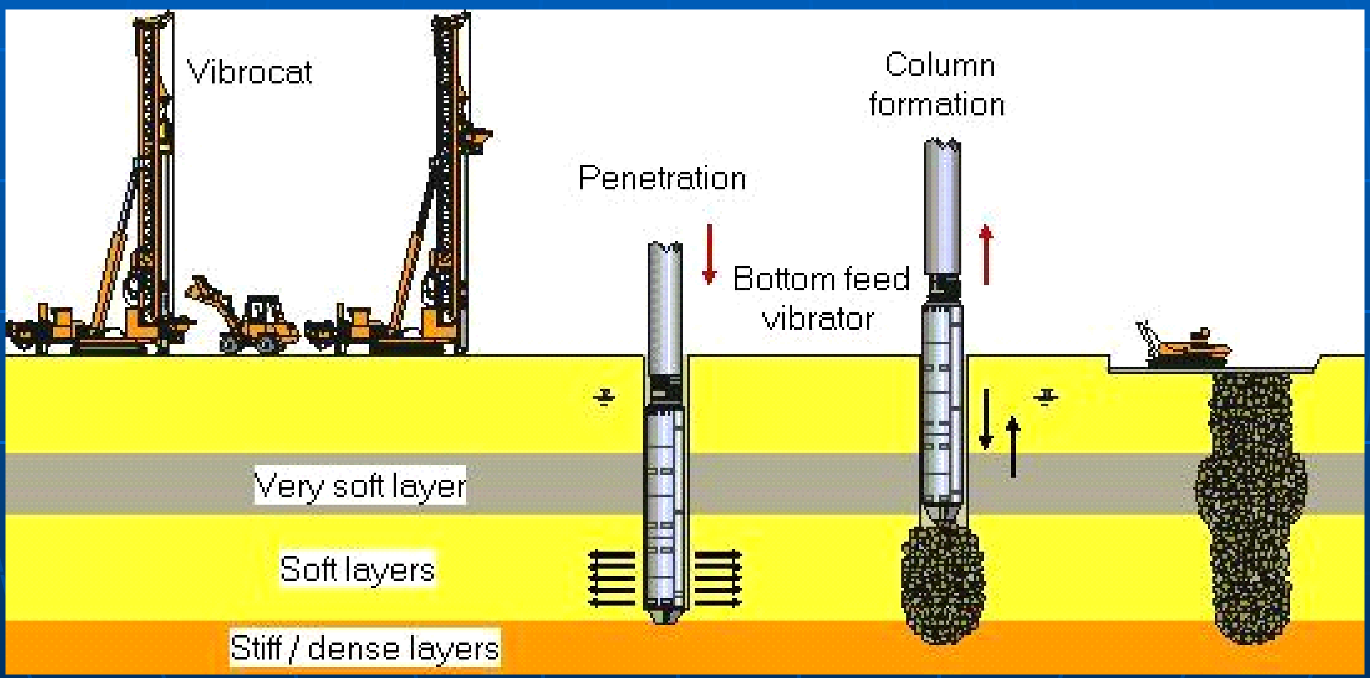


Wet Top-Feed Method of Installation



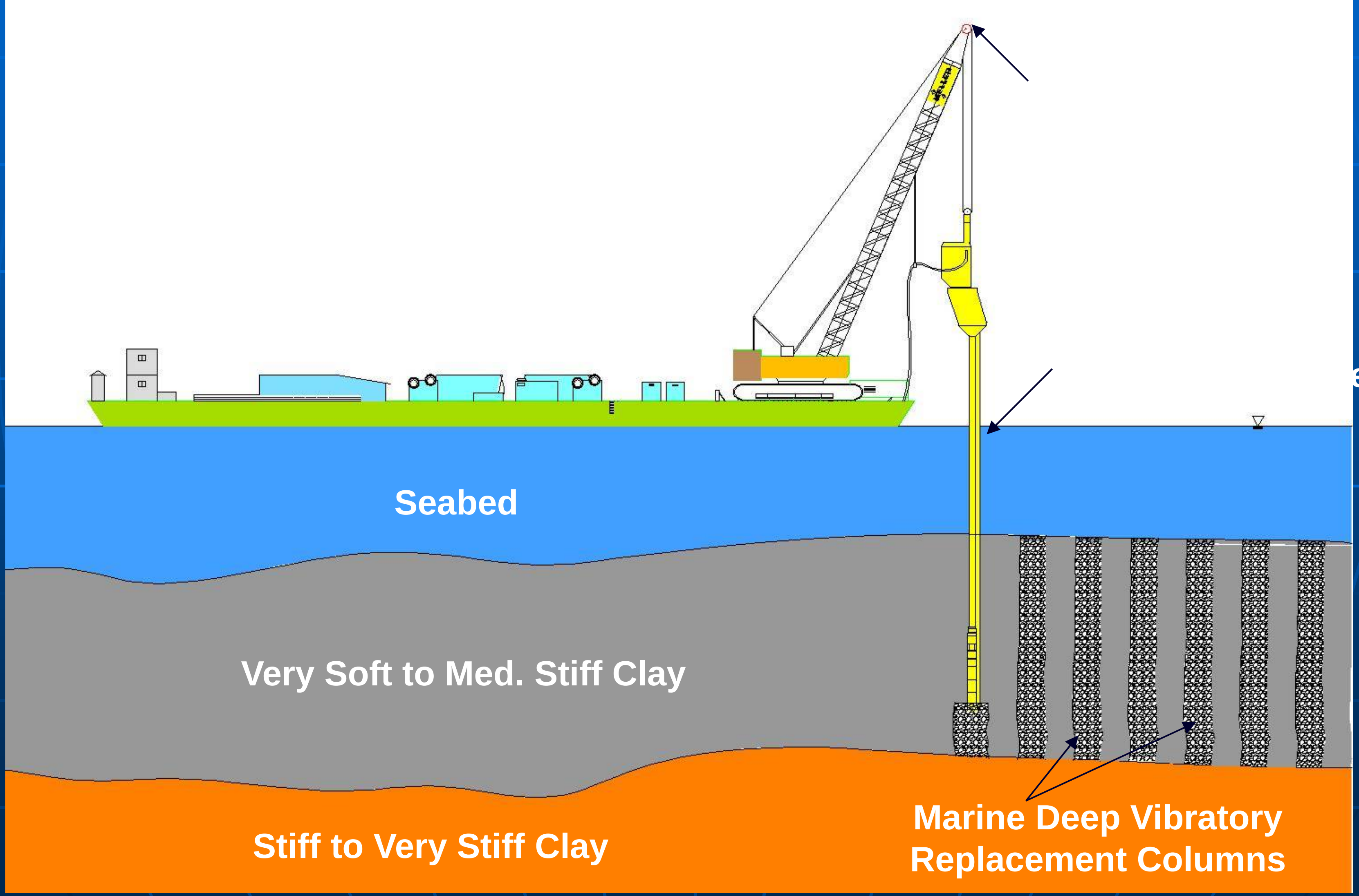
Penetration & Flushing → Column Construction → Completion

Dry Bottom-Feed Method of Installation



Penetration → Delivery and Compaction Process of Stones → Completion

Offshore Installation (Bottom-Feed Method)



Quality Assurance & Quality Check

Real-Time Computerised Monitoring

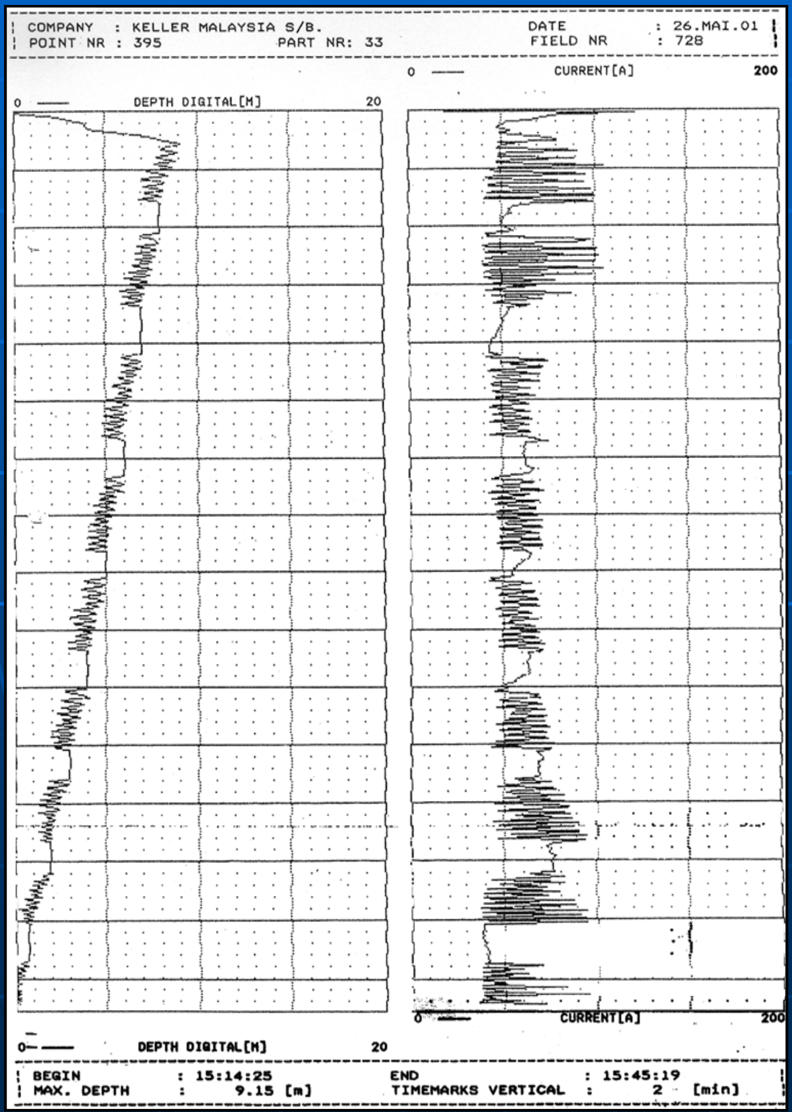
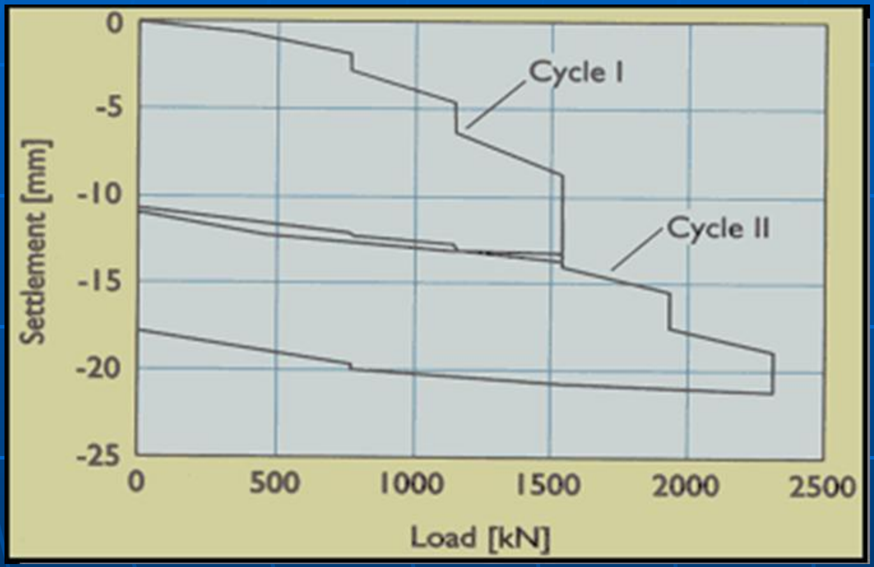


Plate Load Test



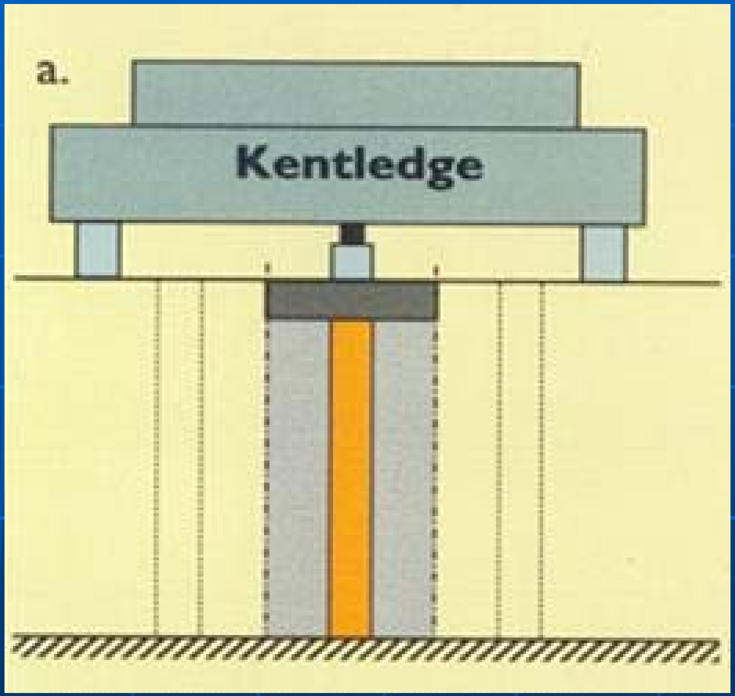
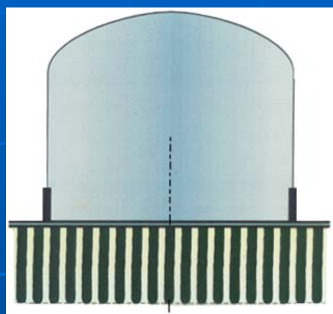


Plate Load Test

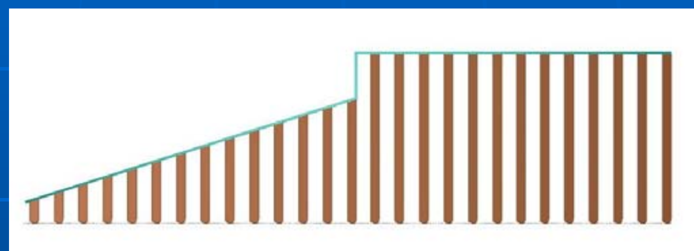
400 Tons load on 4m x 4m ~ 250 kPa

Exposed Vibro Stone columns

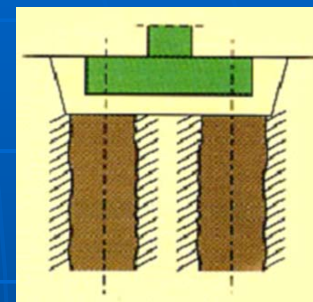
Applications of Vibro Replacement



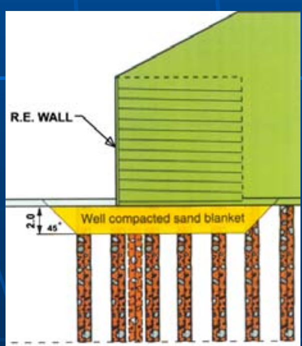
Tank Foundations



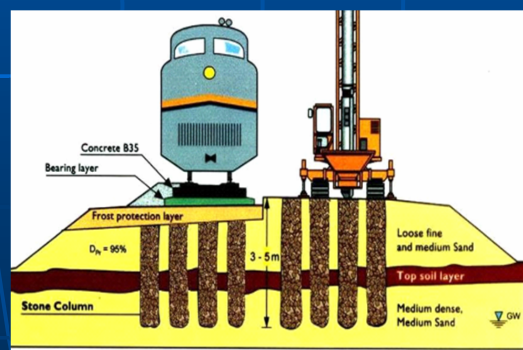
Ports - Slope Stability



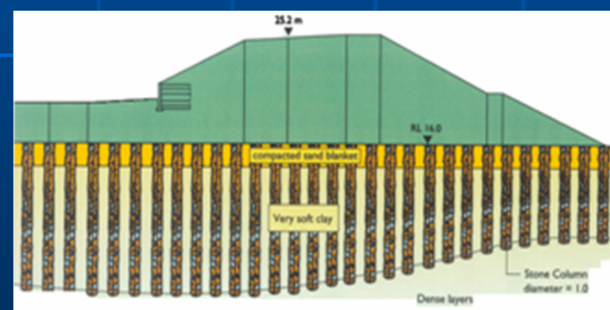
Footings (Isolated / Raft)



Reinforced Earth Walls



Railways



Highway Embankments

Case History – Tank Farm

Oil Tank Farm, Paradeep

- **Background**
  - **Owner: IOCL**
  - **Structure: 15 nos of tanks with 60,000 KL capacity of 79m dia & 13.5m ht**

- **Soil Conditions**
  - **Reclaimed soil in top 3m followed by 3m clay**
  - **Underlain by loose to medium dense fine sands to a depth of 10m**
  - **Dense soil layer at 10m below GL**

Oil Tank Farm, Paradeep

- **Geotechnical Problem**
  - **Bearing Capacity of 16T/m^2 is required**
  - **Tolerable settlement of 200mm**

- **Solution**
  - **Vibro stone Column of diameter 800mm with triangular grid spacing of 2m c/c up to a depth of 10m**
  - **Two extra columns rows around foot print area of tank**

Oil Tank Farm, Paradeep

- **Execution Details**
  - **Total length of stone columns: 1,60,000 linear meter**
  - **At peak 4 rigs were used**
  - **Installation period: 8 months**

Oil Tank Farm, Paradeep

- **Performance & Testing**
  - **Routine group column load tests were performed**
  - **Hydro tests were performed and monitored settlements were below 100mm**

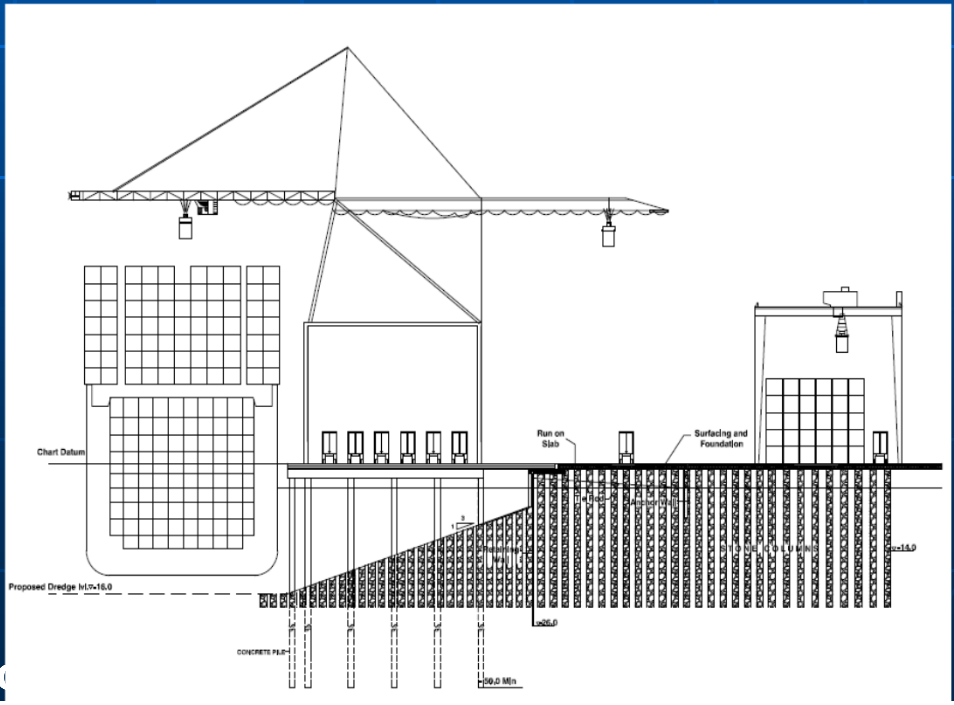
Case History – Port

ICTT, Vallarpadam, Cochin

ICTT, Vallarpadam, Cochin

- **Background**
  - **Owner: Dubai Ports (DP World)**
  - **Structure: 600m long quay wall and associated container yard. The deck has a slope of 1V:3H**

- **Soil Conditions**
  - **2 to 3m of fill followed by 20m thick soft clay**
  - **Followed by medium stiff t**



ICTT, Vallarpadam, Cochin

- **Geotechnical Problem**
  - **Slope stability**
  - **Control the settlement in the associated structures**

- **Solution**
  - **Vibro stone column of dia1100mm with triangular grid spacing of 2.1m c/c**
  - **Vibro stone columns extended up to 22.5m**

ICTT, Vallarpadam, Cochin

- **Execution Details**
  - **Total length of stone columns: 2,35,000 linear meter**
  - **At peak 4 rigs were used**
  - **Installation period: 8 months**

Case History – Shipyard

Pipavav Shipyard, Gujarat

Pipavav Shipyard, Gujarat

- **Background**
  - **Owner: Pipavav Shipyard Limited**
  - **Structure: 300m long quay walls, erection of high capacity goliath cranes, hard standing pavements & approach roads**

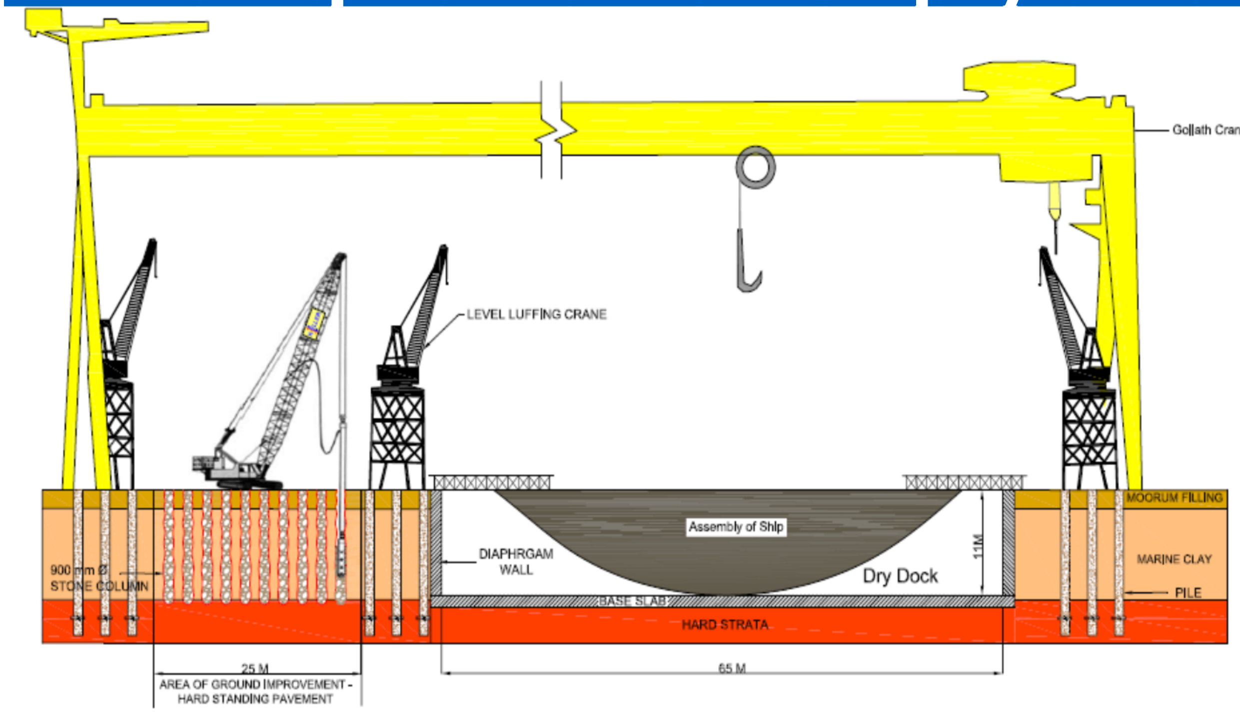
- **Soil Conditions**
  - **Top 2m of subsoil is murrum fill (N ~ 9) followed by 10m to 12m thick marine clay (N ~ 4 to 6)**
  - **Underlain by weathered rock layer (N > 50)**

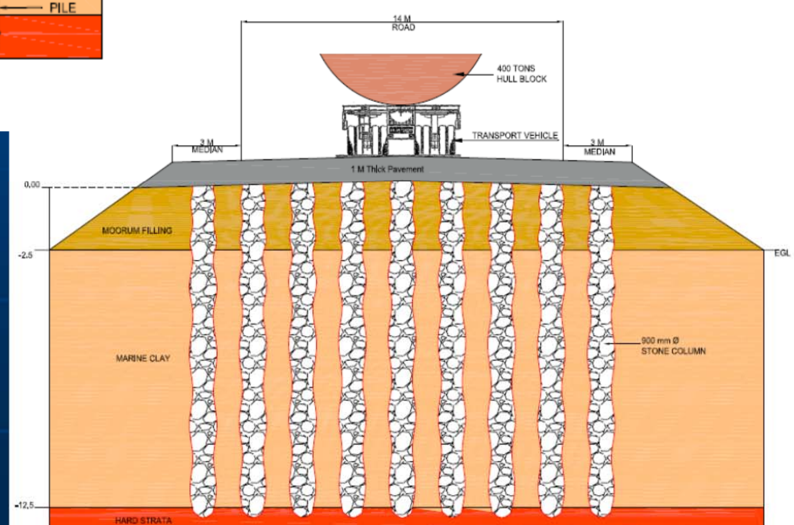
Pipavav Shipyard, Gujarat

- **Geotechnical Problem**
  - **Limit the settlements**
  - **Increase bearing capacity for hard standing pavements**

- **Solution**
  - **Vibro stone column of dia 900mm with triangular grid spacing of 2.5m c/c**
  - **Vibro stone columns extended up to 15m**

Pipavav Shipyard, Gujarat





Pipavav Shipyard, Gujarat

- **Execution Details**
  - **Total length of stone columns: 1,44,000 linear meter**
  - **At peak 4 rigs were used**
  - **Installation period: 10 months**

Case History – Power Plants

NTECL (3x500MW), Chennai

- **Background**
  - **Owner: NTECL (NTPC – TNEB JV)**
  - **Structure: Cooling towers & other ancillary structures**

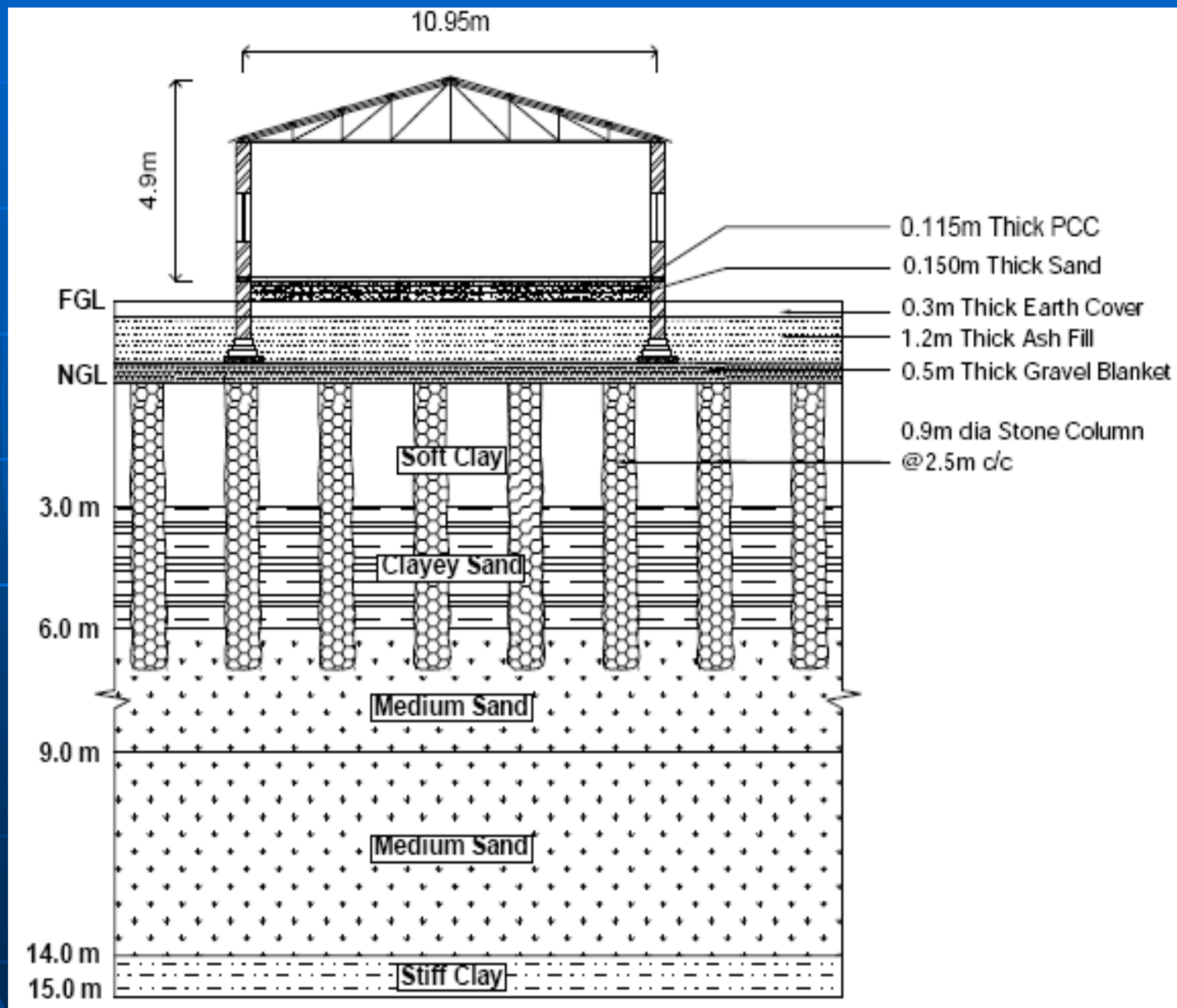
- **Soil Conditions**
  - **Subsoil consists of 7 to 9m thick soft clay (N ~ 0-6) followed by 3m thick medium dense sand (N ~ 12)**
  - **Followed by clayey sand (N ~ 25) & very stiff to hard clay layers**

NTECL (3x500MW), Chennai

- **Geotechnical Problem**
  - o **Increase the bearing capacity**
  - o **Limit the settlements**

- **Solution**
  - o **Vibro stone column of 900mm with triangular grid spacing varying from 2m to 2.5m c/c**
  - o **Vibro stone columns extended up to 11m**

NTECL (3x500MW), Chennai



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ilding

NTECL (3x500MW), Chennai

- **Execution Details**
  - **Total length of stone columns: 3,00,000 lin.m.**
  - **At peak 4 rigs were used**
  - **Installation period: 20 months**

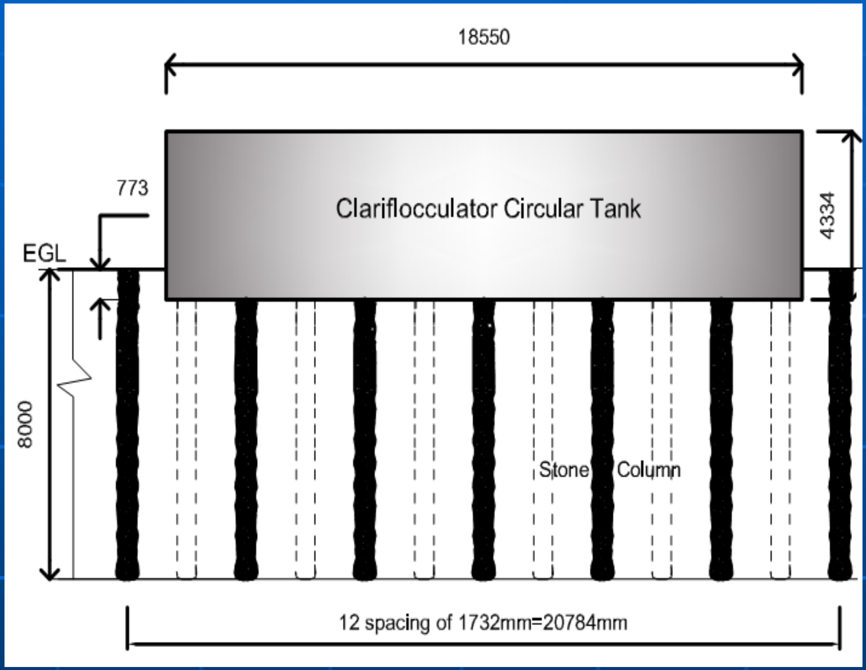
NDPL (108MW), New Delhi

- **Background**
  - **Owner: North Delhi Power Limited (NDPL)**
  - **Structure: Ancillary structures of power plant like Clariflocullator, storage tanks, switch yard, etc.**

- **Soil Conditions**
  - **Loose to medium dense sandy soils (N ~ 5 to 10) to about 10m depth**
  - **Followed by dense silty sand/ sandy silt (N > 15 to 20)**
  - **Site is located in seismic zone IV (PGA = 0.24g)**

NDPL (108MW), New Delhi

- **Geotechnical Problem**
  - o **Increase the bearing capacity**
  - o **Mitigate liquefaction potential**



- **Solution**
  - o **Vibro stone column of 500mm with triangular grid spacing of 2m c/c (dry displacement method)**
  - o **Vibro stone columns extended up to 8 to 12m below EGL**

NDPL (108MW), New Delhi

- **Execution Details**
  - **Total area of treatment: 5,900m²**
  - **Custom-built dry bottom-feed rig used (displacement method)**
  - **Installation period: 8 weeks**

Case History – Railways

Railway Wheel Plant, Chappra, Bihar

- **Background**
  - **Owner: Indian Railways**
  - **Structure: Cast wheel manufacturing unit**

- **Soil Conditions**
  - **Recent fill followed by silty sand layer of thickness 7m**
  - **Soil susceptible to liquefaction (Zone IV – PGA ~ 0.24g)**

Railway Wheel Plant, Chappra, Bihar

- **Geotechnical Problem**
  - **Mitigate liquefaction potential (0.24g)**

- **Solution**
  - **Vibro stone column of diameter 750mmm at 2.8m c/c**
  - **Vibro stone columns extended up to 12m**

Railway Wheel Plant, Chappra, Bihar

- **Execution Details**
  - **Total length of stone columns: 11,000 linear meter**
  - **1 rig was used**
  - **Installation period: 2 months**

Thank You!