IS 15284-1 (2003): Design and construction for ground improvement - Guidelines, Part 1: Stone columns [CED 43: Soil and Foundation Engineering]

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भारतीय मानक

भूमि सुधार के डिजाइन और संरचना — मार्गदर्शी सिद्धांत

भाग 1 पाषाण स्तंभ

Indian Standard

DESIGN AND CONSTRUCTION FOR GROUND IMPROVEMENT — GUIDELINES

PART 1 STONE COLUMNS

ICS 93.020

BUREAU OF INDIAN STANDARDS
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

FOREWORD

This Indian Standard (Part 1) was adopted by the Bureau of Indian Standards, after the draft finalized by the Soil and Foundation Engineering Sectional Committee had been approved by the Civil Engineering Division Council.

The paucity of good construction sites requires the present day engineer to build structures on soils hitherto considered unsuitable due to their poor strength and deformation characteristics. While cost-benefit analysis carried out over a range of foundation solutions may yield the most suitable type of foundation, the end result in a majority of cases may turn out to be in favour of ground improvement especially for structures where tolerable settlement limits are not highly restrictive, such as for wide spread loads which include steel storage tanks for hydrocarbon industry, embankments, fills, etc.

Several ground treatment techniques are available which may meet the twin objective of increasing the bearing capacity with simultaneous reduction of settlements. Reinforcing the ground using stone columns is one of such techniques.

This standard on ground improvement is being published in two parts:

Part 1 Stone columns
Part 2 Preconsolidation using vertical drains (*under preparation*)

The composition of the Committee responsible for the formulation of this standard is given at Annex E.

For the purpose of deciding whether a particular requirement of this standard is complied with the final value observed or calculated is to be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

Indian Standard

DESIGN AND CONSTRUCTION FOR GROUND IMPROVEMENT — GUIDELINES

PART 1 STONE COLUMNS

1 SCOPE

This standard (Part 1) covers the design methodology as well as the construction techniques for installation of stone columns particularly for wide spread loads, such as tanks, embankment and fills. The parameters required for design are also included. The scope is limited to the computation of allowable loads and settlements for wide spread loads.

2 REFERENCES

The Indian Standards given below contain provisions which, through references in the text, constitute provisions of this standard. At the time of publication, the editions indicated were valid. All standards are subject to revision and parties to agreements based on these standards are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below:

IS No.	Title
1892 : 1979	Code of practice for subsurface investigations for foundations (*first revision*)
6403 : 1981	Code of practice for determination of bearing capacity of shallow foundations (*first revision*)
8009 (Part 1) : 1976	Code of practice for calculation of settlements of foundations: Part 1 Shallow foundations subjected to symmetrical static vertical loads

3 TERMINOLOGY

For the purpose of this standard the following definitions shall apply.

3.1 Displacement/Non-displacement Type of Installation Process — If the soil is laterally displaced while making the hole due to driving of a tube or a casing, it is the displacement type of boring. When the soil is taken out during boring, it is non-displacement type of installation.

3.2 Ground Improvement — To improve the load bearing capacity of the loose or soft soil to the required depth by some practical methods.

3.3 Sensitivity of Clay — The ratio of the unconfined compressive strength of clay at its natural state to the remoulded condition.

3.4 Working Stone Column — A stone column forming part of a foundation system of a structure.

3.5 Initial Test Column — Columns, which are not working columns, but are installed for assessing the load carrying capacity of a stone column.

Such columns may be tested either to its ultimate load capacity or to at least 1.5 times the design load. The test is called initial load test.

3.6 Routine Test Column — The column that is selected for load testing and is subsequently loaded for the purpose. The test column may form a working column itself, if subjected to routine load test with loads upto 1.1 times the safe load. This test is called routine load test.

3.7 Ultimate Load — The maximum load which a column can carry before failure of ground or column material, whichever is lower.

3.8 Safe Load — Load derived by applying a factor of safety on the ultimate load capacity of the column or as determined by the column load test.

3.9 Factor of Safety — Ratio of the ultimate load capacity of a column to the safe load capacity of the stone column.

3.10 Allowable Load — The load which may be applied to a stone column after taking into account its ultimate load capacity, column spacing, allowable settlement, etc.

3.11 Working Load — The load assigned to a column as per design.

4 NECESSARY INFORMATION

For the satisfactory design and installation of stone columns, the following information is necessary:

   a) Soil investigation data as laid down in IS 1892 and/or any other relevant Indian Standards. Borelogs supplemented by penetration tests and other *in-situ* test results down to medium to dense or stiff to very stiff stratum incorporating all relevant data down to the investigated depth. The nature of soil should be indicated on the basis of appropriate tests with respect to index properties, shear strength and

compressibility. Soil profiles, wherever required, should also be incorporated.

b) Ground water level and its condition.

c) The general layout of the structure showing its foundation system, loading pattern and intensity as determined from structural analysis.

d) Sufficient information of structures existing nearby.

5 EQUIPMENT AND ACCESSORIES

The equipment and accessories should depend upon the installation methodology intended to be used for constructing the stone columns. The equipments should be selected giving due consideration to the subsoil strata, ground water conditions, type of founding strata, type of structure, the required penetration in the soil, availability of resources and time, etc.

6 SOME IMPORTANT FEATURES OF STONE COLUMN TREATMENT

6.1 Influence of Soil Type

Subsurface soils whose undrained shear strength range from 7 to 50 kpa or loose sandy soils including silty or clayey sands represent a potential class of soils requiring improvement by stone columns. Subsurface conditions for which stone columns are in general not suited include sensitive clays and silts (sensitivity is ≥ 4) which lose strength when vibrated and also where suitable bearing strata for resting the toe of the column is not available under the weak strata.

6.2 Influence of Construction Methodology

The disturbance caused to the soil mass due to a particular method of constructing the stone columns significantly affects the overall behaviour of the composite ground. The availability of equipment, speed of construction and the depth of treatment would normally influence the choice of construction technique.

6.3 Treatment Depth

The treatment depth with stone column for a given soil profile should be so determined that the stone columns extend through the most significant compressible strata that contribute to the settlement of the foundation.

NOTE — Average depth of stone column accomplished in India may be around 15.0 m or so, although with equipment modification, higher depths beyond 20 m may become a possibility in future.

6.4 Area of Treatment

Stone columns work most effectively when used for large area stabilization of the soil mass. Their application in small groups beneath building foundations is limited and is not being used. Thus, large loaded areas which apply uniform loading on foundation soils, such as beneath embankments, tank farms and fills represent a major area of application.

6.5 Termination

End bearing is not a speciflc requirement for stone columns. However, they should extend through the soft compressible strata as indicated in 6.4. The soil near the ground surface has a dominating influence on settlement and ultimate bearing capacity of stone columns.

7 BASIC DESIGN PARAMETERS

7.1 Stone Column Diameter, D

7.1.1 Installation of stone columns in soft cohesive soils is basically a self compensating process that is softer the soil, bigger is the diameter of the stone column formed. Due to lateral displacement of stones during vibrations/ramming, the completed diameter of the hole is always greater than the initial diameter of the probe or the casing depending upon the soil type, its undrained shear strength, stone size, characteristics of the vibrating probe/rammer used and the construction method.

7.1.2 Approximate diameter of the stone column in the field may be determined from the known compacted volume of material required to fill the hole of known length and maximum and minimum densities of the stone.

7.2 Pattern

Stone columns should be installed preferably in an equilateral triangular pattern which gives the most dense packing although a square pattern may also be used. A typical layout in an equilateral triangular pattern is shown in Fig. 1.

7.3 Spacing

7.3.1 The design of stone columns should be site specific and no precise guidelines can be given on the maximum and the minimum column spacing. However, the column spacing may broadly range from 2 to 3 depending upon the site conditions, loading pattern, column factors, the installation technique, settlement tolerances, etc.

7.3.2 For large projects, it is desirable to carry out field trials to determine the most optimum spacing of stone columns taking into consideration the required bearing capacity of the soil and permissible settlement of the foundation.
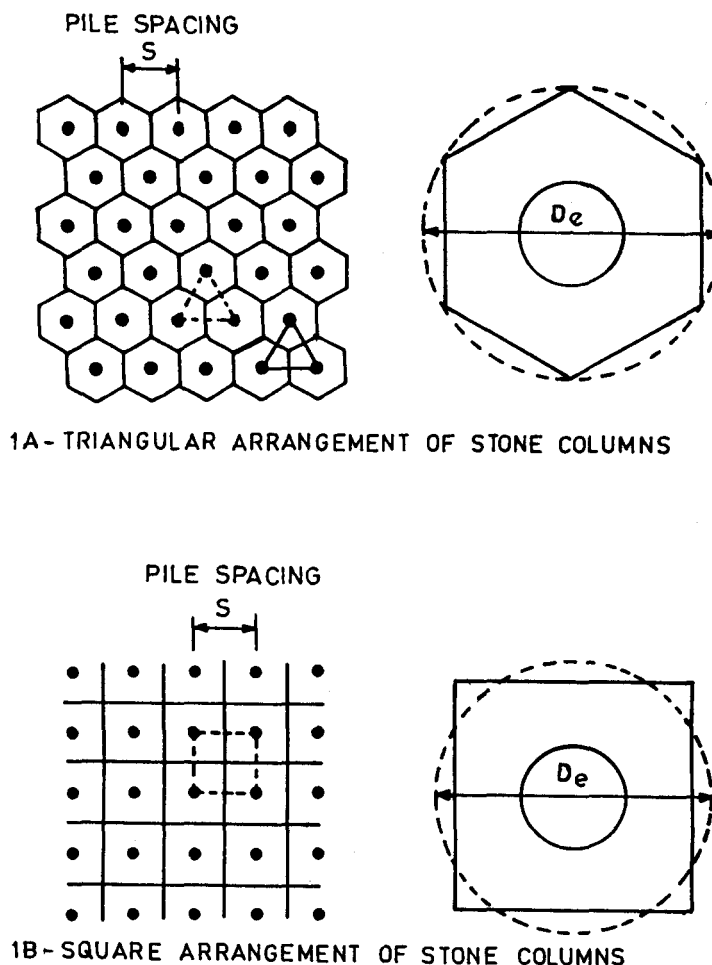
PILE SPACING

1A- TRIANGULAR ARRANGEMENT OF STONE COLUMNS

PILE SPACING

1B- SQUARE ARRANGEMENT OF STONE COLUMNS

Fig. 1 Various Patterns of Stone Columns

7.4 Equivalent Diameter

7.4.1 The tributory area of the soil surrounding each stone column forms regular hexagon around the column. It may be closely approximated by an equivalent circular area having the same total area (*see* Fig. 1).

7.4.2 The equivalent circle has an effective diameter (D_e) which is given by following equation:

$$D_c = 1.05\ S \text{ for an equilateral triangular pattern, and}$$
$$= 1.13\ S \text{ for a square pattern}$$

where

S = spacing of the stone columns.

The resulting equivalent cylinder of composite ground with diameter D_e enclosing the tributory soil and one stone column is known as the unit cell.

7.5 Replacement Ratio (a_s)

7.5.1 For purpose of settlement and stability analysis, the composite ground representing an infinitely wide loaded area may be modeled as a unit cell comprising the stone column and the surrounding tributory soil. To quantify the amount of soil replaced by the stone, the term replacement ratio, a_s, is used. Replacement ratio (a_s) is given by:

$$a_s = \frac{A_s}{A} = \frac{A_s}{A_s + A_g}$$

where

A_s = area of the stone column,

A_g = area of ground surrounding the column, and

A = total area within the unit cell.

3

7.5.2 The area replacement ratio may also be expressed as follows:

$$a_s = 0.907 \, (D/S)^2$$

where the constant 0.907 is a function of the pattern used which, in this case, is the commonly employed equilateral triangular pattern.

7.6 Stress Concentration Factor (n)

7.6.1 Stress concentration occurs on the stone column because it is considerably stiffer than the surrounding soil. From equilibrium considerations, the stress in the stiffer stone columns should be greater than the stress in the surrounding soil.

7.6.2 The stress concentration factor, n, due to externally applied load σ, is defined as the ratio of average stress in the stone column, σ_s, to the stress, σ_g, in the soil within the unit cell,

$$n = \frac{\sigma_s}{\sigma_g}$$

The value of n generally lie between 2.5 and 5 at the ground surface. The stress concentration factor (n) increases with time of consolidation and decreases along the length of the stone column. Higher n value at ground surface may result if load is applied to the composite ground through a rigid foundation as compared to the flexible foundation.

7.6.3 The stress concentration factor, n, may be predicted using elastic theory as a function of the modular ratio of the stone and the clay assuming equal vertical displacements. However, as the modular ratio can vary within wide limits, it should be selected from **7.6.2**.

8 FAILURE MECHANISMS

8.1 Failure mechanism of a single stone column loaded over its area significantly depends upon the length of the column. For columns having length greater than its critical length (that is about 4 times the column diameter) and irrespective whether it is end bearing or floating, it fails by bulging (see Fig. 2 A). However, column shorter than the critical length are likely to fail in general shear if it is end bearing on a rigid base (see Fig. 2B) and in end bearing if it is a floating column as shown in Fig. 2C.

8.2 In practice, however, a stone column is usually loaded over an area greater than its own (see Fig. 3) in which case it experiences significantly less bulging leading to greater ultimate load capacity and reduced settlements since the load is carried by both the stone column and the surrounding soil.

NOTE — The above failure mechanisms apply to stone columns installed in homogeneous soils. Practical situations may arise where isolated zones of very soft cohesive soils may result in significant bulging at both shallow and deep depths and hence, this should be duly considered wherever necessary.

8.4 Wherever interlayering of sand and clay occurs, and if the sand layer is thick enough as compared to the size of the loaded area, the general compaction achieved by the action of the installation of the stone columns may provide adequate rigidity to effectively disperse the applied stresses thereby controlling the settlement of the weak layer. However, effective reduction in settlement may be brought about by

2A-LONG STONE COLUMN WITH FIRM OR FLOATING SUPPORT-BULGING FAILURE

2B-SHORT COLUMN WITH RIGID BASE: SHEAR FAILURE

2C-SHORT FLOATING COLUMN: PUNCHING FAILURE
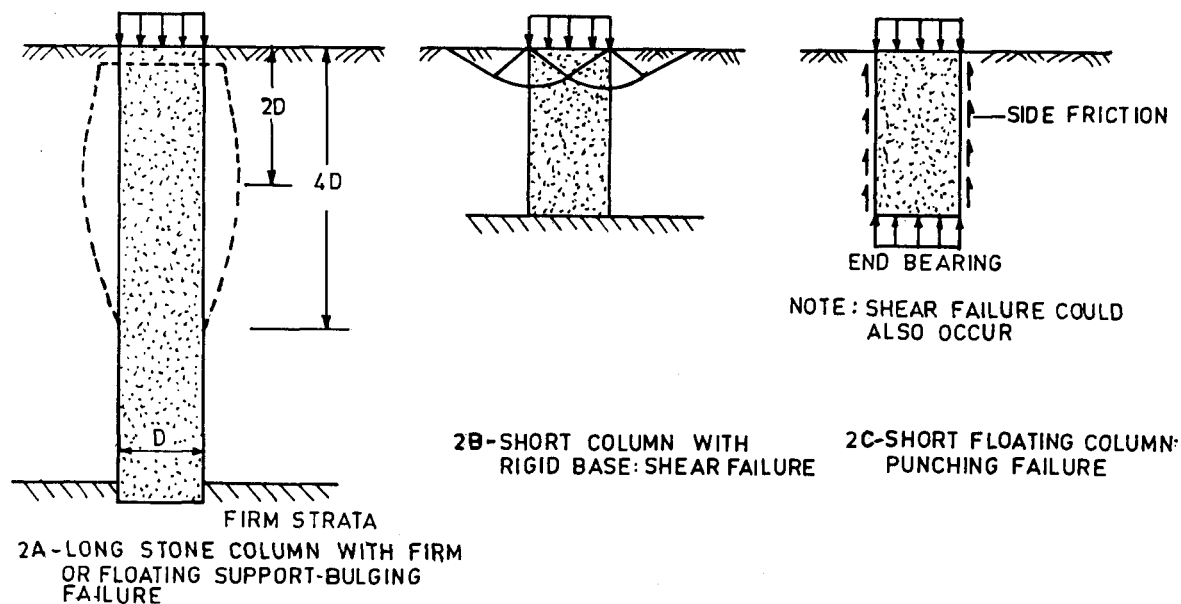
NOTE: SHEAR FAILURE COULD ALSO OCCUR

FIG. 2 FAILURE MECHANISMS OF A SINGLE STONE COLUMN IN A HOMOGENOUS SOFT LAYER
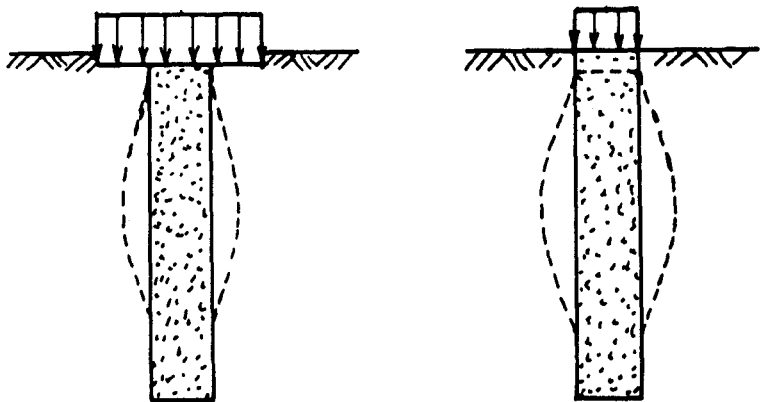
FIG. 3 DIFFERENT TYPE OF LOADINGS APPLIED TO STONE COLUMNS

carrying out the treatment of stone columns through the compressible layer.

When clay is present in the form of lenses and if the ratio of the thickness of the lense to the stone column diameter is less than or equal to 1, the settlement due to presence of lenses may be insignificant.

8.5 In mixed soils, the failure of stone columns should be checked both for predominently sandy soils as well as the clayey soil, the governing value being lower of the two calculated values.

9 DESIGN CONSIDERATIONS

9.1 General

By assuming a triaxial state of stress in the stone column and both the column and the surrounding soil at failure, the ultimate vertical stress, σ_1, which the stone column can take, may be determined from the following equation:

$$\frac{\sigma_1}{\sigma_3} = \frac{1+Sin\phi_s}{1-Sin\phi_s}$$

where

σ_3 = lateral confining stress mobilized by the surrounding soil to resist the bulging of the stone column;

ϕ_s = angle of internal friction of the stone column; and

σ_1/σ_3 = coefficient of passive earth pressure k_p of the stone column.

This approach assumes a plane strain loading condition (such as passive resistance mobilized behind a long retaining wall) and hence does not realistically consider the three dimensional geometry of a single stone column.

9.1.1 The bearing capacity of an isolated stone column or that located within a group may be computed using

the other established theories also. Besides the passive resistance mobilized by the soil, the increase in capacity of the column due to surcharge should be taken into consideration. In addition, capacity increase due to soil bearing should also be taken into account.

9.1.2 Particular attention should be paid to the presence of very weak organic clay layers of limited thickness where local bulging failure may take place (*see* Fig. 4). Therefore, capacity of column in such weak clays should also be checked even if they are below the critical depth.

9.2 Adjacent Structures

9.2.1 When working near existing structures, care should be taken to avoid damage to such structures by suitable measures.

9.2.2 In case of deep excavation adjacent to stone columns, prior shoring or other suitable arrangement should be done to guard against the lateral movement of soil or loss of confining soil pressure.

9.3 Ultimate Load Capacity and Settlement

9.3.1 The ultimate load carrying capacity of stone column may be estimated approximately on the basis of soil investigation data or by test loading. However, it should be preferably determined by an initial load test on a test column specifically installed for the purpose and tested to its ultimate load particularly in a locality where no such previous experience exists.

9.3.2 Procedure for estimating the load capacity and settlement of a single column is given in Annex A and Annex B, respectively. Any other alternate formulae with substantially proven reliability depending upon the sub-soil characteristics and the method of installation, may also be used.

9.4 Environmental Factors

Design considerations should take into account the environmental factors, such as presence of aggressive
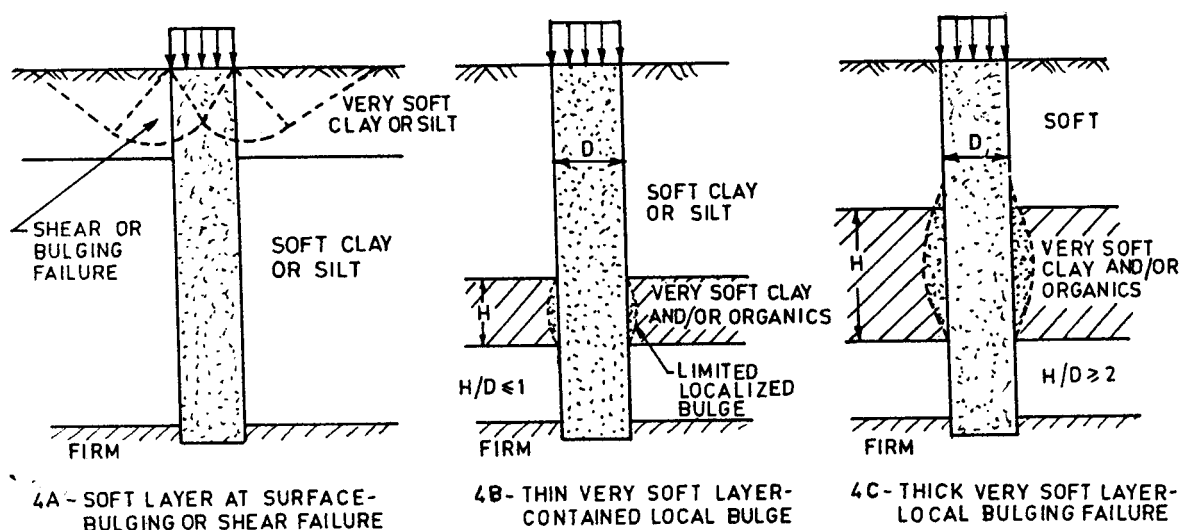
FIG. 4 STONE COLUMN FAILURE MECHANISMS IN NON-HOMOGENOUS COHESIVE SOIL

chemicals in the sub-soil and ground water, an artesian conditions, etc.

9.5 Load Test Results

The ultimate load capacity of single column may be determined from load tests with reasonable accuracy. The settlement of a stone column obtained at safe/working load from load test results on a single column should not be directly used in forecasting the settlement of the structure unless experience from similar foundations in similar soil conditions on its settlement behaviour is available. The average settlement may be assessed on the basis of sub-soil data and loading details of the structures as a whole using the principles of soil mechanics.

9.6 Factor of Safety

9.6.1 The following factors should be considered for selecting a suitable factor of safety:

a) Reliability of the value of ultimate load carrying capacity of the column,

b) The type of superstructure and the type of loading,

c) Allowable total and differential settlement of the structure, and

d) The manner of load transfer from stone column to the soil.

9.6.2 It is desirable that the ultimate capacity of column is obtained from an initial load test. The minimum factor of safety for such a load test should be 2.5.

9.6.3 When ultimate capacity is derived from soil mechanics considerations, the minimum factor of safety recommended in each formula should be applicable.

10 INSTALLATION TECHNIQUES

The construction of stone columns involves creation of a hole in the ground which is later filled with granular material. The granular fill consisting of stone or stone sand mixture of suitable proportion, is compacted by suitable means to create a compacted column of required strength. The recommended installation techniques are given at Annex C.

11 GRANULAR BLANKET

11.1 Irrespective of the method used to construct the stone columns, the blanket laid over the top of the stone columns should consist of clean medium to coarse sand compacted in layers to a relative density of 75 to 80 percent.

11.2 Minimum thickness of the compacted sand blanket should be 0.5 m. This blanket should be exposed to atmosphere at its periphery for pore water pressure dissipation.

11.3 After ensuring complete removal of slush deposited during boring operations, a minimum depth of 0.5 m, preferably 0.75 m below the granular blanket should be compacted by other suitable means, such as rolling/tamping to the specified densification criteria.

12 FIELD CONTROLS

12.1 In the methods involving boring the set criteria and the consumption of granular fill form the main quality control measures for the columns constructed by the non-displacement technique. The set criteria

6

should be established as per **C-1.1** (m). For ascertaining the consumption of fill, the diameter of the column as formed during field trials should be measured in its uppermost part for a depth of four diameters and average of these observations taken as the column diameter.

12.2 In the case of vibroflots, the following minimum field controls should be observed:

a) Vibroflot penetration depth including the depth of embedment in firm strata,

b) Monitoring of volume of backfill added to obtain an indication of the densities achieved, and

c) Monitoring of ammeter or hydraulic pressure gauge readings to verify that the maximum possible density has been achieved in case of vibrofloted columns.

13 FIELD LOADING TESTS

13.1 Irrespective of the method used to construct the stone columns, the initial load tests should be performed at a trial test site to evaluate the load-settlement behaviour of the soil-stone column system. The tests should be conducted on a single and also on a group of minimum three columns.

13.2 For the initial load tests, in order to simulate the field conditions of compaction of the intervening soil, a minimum of seven columns for a single column test and twelve columns for three column group test may be constructed for triangular pattern as shown in Fig. 5.

13.3 The diameter of the circular concrete footing or equivalent steel plate of adequate thickness and rigidity may be based on the effective tributory soil area of stone column for a single column test and three times the effective area of single column for a three column group test. In each case, the footing may cover the equivalent circular effective area centrally.

13.4 The initial and final soil conditions at the trial site should be investigated by drilling at least one borehole and one static cone test/pressure meter test/dynamic cone test prior and subsequent to the installation of columns as per **13.2**. All these tests including the standard penetration test, field vane shear tests and collection of undisturbed/disturbed samples and laboratory testing on the samples should be as per relevant Indian Standards.
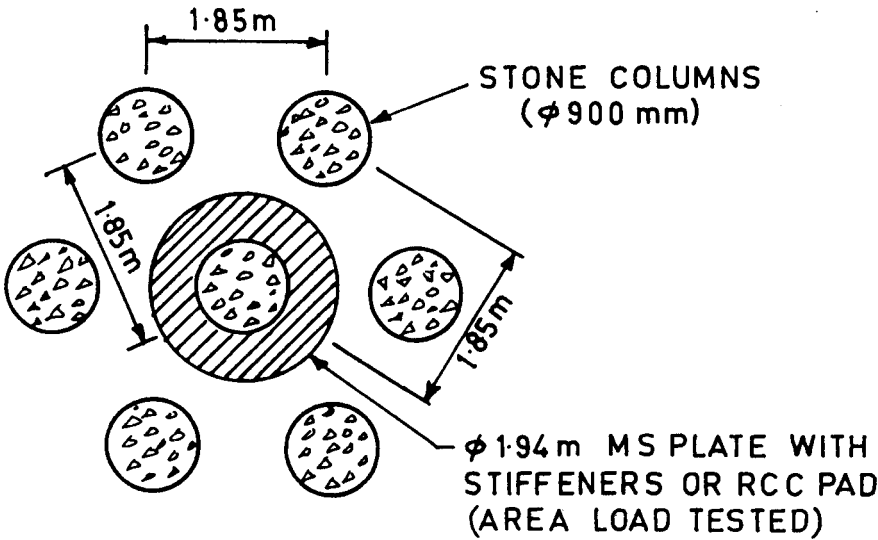
13.5 A granular blanket of medium to coarse sand having thickness not less than 300 mm should be laid over the test column(s) as per **11**. Over the blanket, a properly designed footing should be laid. The footing may be cast away from the test site and transported to the test location so as to fix it properly over the sand blanket.
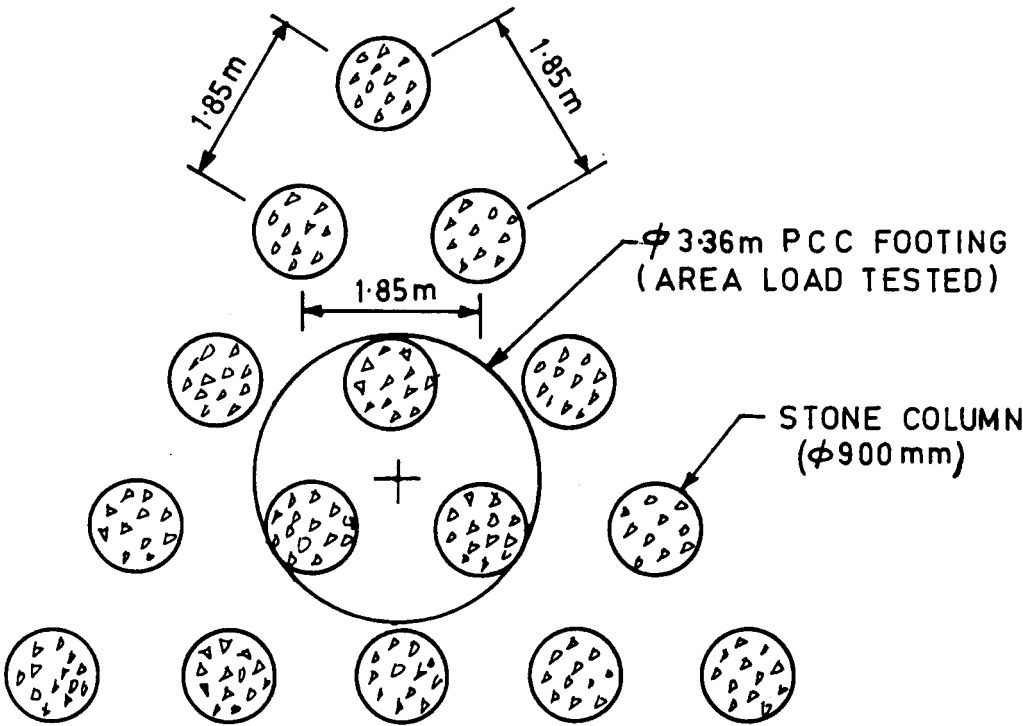
13.6 In case high water table conditions exist at site, the water level during the tests should be maintained at the footing base level by dewatering.

13.7 Following procedure should be followed for application of load:

a) The load should be applied to the footing by a suitable kentledge (*see* Fig. 6), taking care to avoid impact, fluctuations or eccentricity.

b) The kentledge should be minimum 1.30 times the maximum test load.

c) Load settlement observations should be taken to 1.5 times the design load for a single column and three column group test respectively.

d) The settlements should be recorded by four dial gauges (sensitivity less than or equal to 0.02 mm) fixed at diametrically opposite ends of the footing.

e) Each stage of loading should be near about 1/5 of the design load and should be maintained till the rate of settlement is less than 0.05 mm/h at which instant the next stage of loading should be applied.

f) The design as well as the maximum test load should be maintained for a minimum period of 12 h after stabilization of settlement to the rate as given in **13.7 (e)**.

g) Load settlement and time settlement relationships should be plotted from the settlements observed for each increment of load at intervals of 1 min, 2 min, 4 min, 8 min, 16 min, ½ h, 1 h, 1½ h, 2 h, 3 h, 4 h, and so on till the desired rate of settlement has been achieved. The time intervals may be suitably modified if so desired.

h) The test load should be unloaded in five stages. At each stage enough time should be allowed for settlements to stabilize.

j) The load test should be considered acceptable if it meets the following settlement criteria:

   i) 10 to 12 mm settlement at design load for a single column test, and

   ii) 25 to 30 mm settlement at the design load for a three column group test.

k) For routine load test few job columns (say 1 test for 625 m² area) may be tested upto 1.1 times the design load intensity with minimum kentledge of 1.3 times the design load.

1·85m

STONE COLUMNS
(φ 900 mm)

1·85m

1·85m

φ 1·94 m MS PLATE WITH
STIFFENERS OR RCC PAD
(AREA LOAD TESTED)

5 A- SINGLE COLUMN TEST

1·85 m

1·85m

1·85m

φ 3·36m PCC FOOTING
(AREA LOAD TESTED)

STONE COLUMN
(φ 900 mm)

5 B-THREE COLUMN GROUP TEST
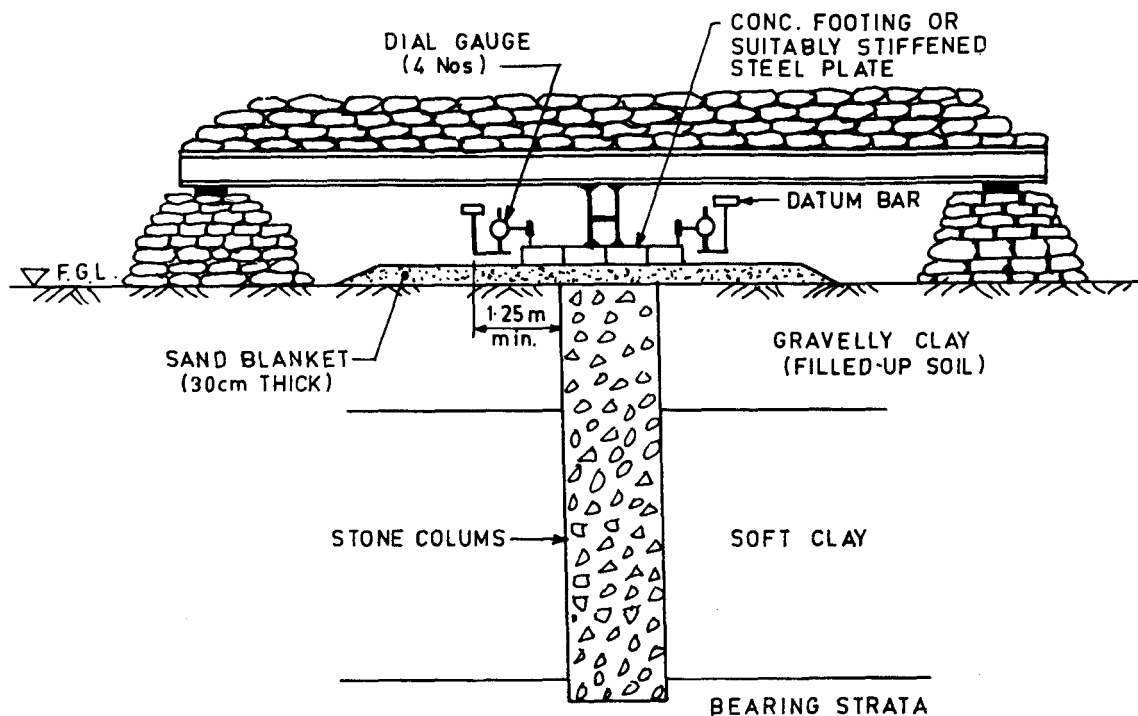
Fig. 5 Arrangement of Columns

FIG. 6 SECTION SHOWING LOADING ARRANGEMENT FOR A SINGLE COLUMN TEST

14 RECORDING OF DATA

14.1 A competent inspector should be appointed at site to record necessary information during installation of stone columns and the data to be recorded may include the following:

a) Sequence of installation of stone columns in a group,

b) Spacing of stone columns,

c) The type and size of rammer and its stroke,

d) Dimensions of the stone column,

e) Depth of installation,

f) Complete record of blow counts for each stone charge and also the overall total number of blows for compaction of stones,

g) The final set for last five blows or as may be specified for each stone charge,

h) Time taken for completing each stone column including withdrawal of casing, and

j) Any other important observation during installation and after withdrawal of casing tube.

14.2 Typical data sheet for recording stone column data is given in Annex D

ANNEX A

(Clause 9.3.2)

ESTIMATION OF LOAD CAPACITY OF A COLUMN

A-1 STONE COLUMNS IN COHESIVE SOILS

Load capacity of the treated ground may be obtained by summing up the contribution of each of the following components for wide spread loads, such as tankages and embankments:

a) Capacity of the stone column resulting from the resistance offered by the surrounding soil against its lateral deformation (bulging) under axial load,

b) Capacity of the stone column resulting from increase in resistance offered by the surrounding soil due to surcharge over it, and

c) Bearing support provided by the intervening soil between the columns.

A-1.1 Capacity Based on Bulging of Column

Considering that the foundation soil is at failure when stressed horizontally due to bulging of stone column, the limiting (yield) axial stress in the column is given by the sum of the following:

$$\sigma_v = \sigma_{rL} Kp_{col}$$
$$\sigma_v = (\sigma_{ro} + 4C_u) Kp_{col} \qquad \ldots (1)$$

where

σ_v = limiting axial stress in the column when it approaches shear failure due to bulging, and

σ_{rL} = limiting radial stress
   = $\sigma_{ro} + 4C_u$

where

C_u = undisturbed undrained shear strength of clay surrounding the column, and

σ_{ro} = initial effective radial stress
   = $K_o \sigma_{vo}$

where

K_o = average coefficient of lateral earth pressure for clays equal to 0.6 or alternatively, as determined from the relationship $K_o = 1\text{-}sin \phi$, where ϕ is the effective angle of internal friction of soil, and

σ_{vo} = average initial effective vertical stress considering an average bulge depth as 2 times diameter of the column (*see* Fig. 2a), that is $\sigma_{vo} = \gamma\, 2D$

where

γ = effective unit weight of soil within the influence zone.

$$Kp_{col} = \tan^2(45° + \frac{\phi_c}{2})$$

where

ϕ_c = angle of internal friction of the granular column material and it may vary depending upon angularity, surface characteristics and density of column material. Value applicable for the stones intended to be used as backfill material may be determined using large shear box tests or laboratory shear test. In absence of such tests, the design may be based on the best engineering judgement. As a broad guide, the ϕ_c may range from 38° to 42° depending upon the compactness achieved during construction of stone columns.

Yield load = $\sigma_v \pi/4\, D^2$

Safe load on column

alone $Q_1 = (\sigma_v \pi/4\, D^2)/2 \quad \ldots (2)$

where 2 is the factor of safety.

A-1.2 Surcharge Effect

a) Initially, the surcharge load is supported entirely by the rigid column. As the column dilates some load is shared by the intervening soil depending upon the relative rigidity of the column and the soil. Consolidation of soil under this load results in an increase in its strength which provides additional lateral resistance against bulging.

b) The surcharge load may consist of sand blanket and sand pad (being applicable to tank foundations). If thicknesses of these elements are not known, the limiting thickness of the surcharge loading as represented by the safe bearing capacity of the soil may be considered.

c) The increase in capacity of the column due to surcharge may be computed in terms of increase in mean radial stress of the soil as follows:

$$\Delta\sigma_{ro} = \frac{q_{safe}}{3} (1 + 2K_0) \qquad \ldots (3)$$

10

where $\Delta\sigma_{ro}$ is the increase in mean radial stress due to surcharge, and q_{safe} is the safe bearing pressure of soil with the factor of safety of 2.5 (*see* IS 6403)

$$q_{safe} = C_u N_c/2.5$$

Increase in ultimate cavity expansion stress $= \Delta\sigma_{ro} Fq'$

where

Fq = vesic's dimension less cylinderical cavity expansion factor

Fq' = 1 for $\phi_g = 0$

Increase in yield stress of the column $= Kp_{col}\Delta\sigma_{ro}$

d) Allowing a factor safety of 2, increase in safe load of column, Q_2 is given by the following formula:

$$Q_2 = \frac{Kp_{col}\Delta\sigma_{ro}A_s}{2} \qquad \ldots (4)$$

The surcharge effect is minimum at edges and it should be compensated by installing additional columns in the peripheral region of the facility.

A-1.3 Bearing Support Provided by the Intervening Soil

This component consists of the intrinsic capacity of the virgin soil to support a vertical load which may be computed as follows:

Effective area of stone column
including the intervening soil
for triangular pattern $= 0.866 S^2$

Area of intervening soil for each column, A_g is given by the following formula:

$$A_g = 0.866 S^2 - \frac{\pi D^2}{4}$$

Safe load taken by the
intervening soil, Q_3 = $q_{safe} A_g$ $\qquad \ldots (5)$

Overall safe load on each column
and its tributary soil $= Q_1 + Q_2 + Q_3$.

NOTE — The number of columns to be provided under a structure may be obtained if the total load to which the structure is subjected to and the reduction in settlements required considering the permissible total and differential settlements for it are known.

A-2 STONE COLUMNS IN MIXED SOILS

A-2.1 In soils having both C and ϕ, the capacity may

be estimated by using Bell's formula for passive pressure:

$$\sigma_{rL} = p_p = \gamma z k_p + 2C_u \sqrt{k_p} \qquad \ldots (1)$$

where

p_p = passive pressure,

z = average bulge depth

= 2 times the column diameter, and

k_p = passive pressure coefficient of soil

= $(1 + sin \phi_g)/(1 - sin \phi_g)$

where

ϕ_g = angle of internal friction of soil.

Limiting axial stress in the column, when it approaches shear failure due to bulging σ_v is given by the following formula:

σ_v = $\sigma_{rL} Kp_{col}$

= $\sigma_{rL} (1 + sin \phi_c)/(1 - sin \phi_c)$

Safe load on column, Q_1 = $\sigma_v \dfrac{\pi/4 D^2}{2}$ $\qquad \ldots (2)$

A-2.2 The surcharge effect (Q_2) and bearing support of the intervening soil (Q_3) may be obtained as per A-1.3.

A-3 Determination of Column Spacing

A-3.1 From the plan area of the structure and the number of columns as assessed in **A-1.3**, area per column is arrived at. This, in turn, will lead to effective spacing between the columns depending upon the pattern of columns as follows:

Pattern	Area for Column
Triangular	0.866 S^2
Square	1.0 S^2

A-3.2 Design calculations should be repeated till there is convergence of the assumed and the calculated column spacing. One or two trials may be required to achieve an acceptable degree of convergence.

A-3.3 Additional stone columns may be required inside and outside the periphery of the loaded area considering pressure distribution, presence/absence of surcharge and permissible or expected settlement of the structure. These additional columns may be provided either as rings or at a closer spacing for an appropriate distance inside as well as outside the periphery of the loaded area.

A-3.4 The load capacity of the stone columns computed as in accordance with A-1.3 should be verified by load test as per **13**.

ANNEX B

(*Clause* 9.3.2)

SETTLEMENT ANALYSIS BY THE REDUCED STRESS METHOD

B-1 SETTLEMENT ANALYSIS

B-1.1 Settlement of the untreated ground should be computed as per IS 8009. Settlements of the treated ground may be estimated using the reduced stress method based on the stress concentration factor n and the replacement ratio, a_s. Stress concentration factor should be suitably arrived as per **7.6**. Area replacement ratio may be obtained from the column diameter and the spacing of stone columns (*see* **7.5**). Following this, the settlement of the treated ground and reduction factor β, can be worked out as follows:

a) The applied stress, σ, is shared between the columns and the surrounding soft ground in proportion to the relative stiffness of the two materials, the cross-sectional area of the columns (A_s) and their spacing.

b) Sharing of the applied stress between the column and the tributary soil is expressed in terms of the stress concentration ratio, n, given below:

$$n = \frac{\sigma_s}{\sigma_g}$$

where

σ_s = vertical stress in compacted columns, and

σ_g = vertical stress in surrounding ground.

c) If A_g is the plan area of the soil for columns, then:

$$(A_s + A_g)\,\sigma = A_s\,\sigma_s + A_g\,\sigma_g$$

d) The replacement of soil with stone is expressed in terms of the replacement ratio, a_s:

$$a_s = \frac{A_s}{A_s + A_g}$$

e) The sharing of applied load between the soil and stone column is determined from the following formulae:

$$\sigma_g = \frac{\sigma}{1+(n-1)\,a_s}$$

$$= \mu_g\,\sigma$$

$$\sigma_g = \frac{n\,\sigma}{1+(n-1)\,a_s}$$

$$= \mu_s\,\sigma$$

f) Consolidation settlement of the composite (treated) soil S_t is given by:

$$S_t = m_v\,\sigma_g\,H$$

$$= m_v\,\mu_g\,\sigma\,H$$

where

m_v = modulus of volume decrease of soil, and

H = thickness of treated soil.

NOTE — This is based on the assumption that the settlement of the strata underlying the column tip is added to the settlement of the reinforced ground.

g) Consolidation settlement S of the unreinforced ground is computed from the one dimensional consolidation theory as given below:

$$S = m_v\,\sigma\,H$$

h) Settlement reduction ratio β is defined as:

$$\beta = \frac{\text{Settlement of treated soil, } S_t}{\text{Settlement of untreated soil, } S}$$

$$\beta = \frac{S_t}{S} = \frac{1}{1+(n-1)a_s}$$

ANNEX C

(*Clause* 10)

INSTALLATION TECHNIQUES OF STONE COLUMNS

C-1 NON-DISPLACEMENT METHOD

In this method, boring can be accomplished by anyone of the techniques as specified in **C-1.1** to **C-1.3**.

C-1.1 Bailer and Casing Method

a) In this method, the borehole is advanced by using a bailer while its sides are retained by a casing.

b) To minimize disturbance at the bottom of the hole and to avoid loss of ground due to suction, the water level in the casing should be maintained at around 2.0 m above the surrounding ground water level.

c) Care should be taken to ensure that during drilling, the casing is always ahead of the boring in order to avoid formation of excess diameter of borehole.

d) To avoid suction effects, the bailer diameter should be 75 mm to 100 mm less than the internal diameter of the casing.

e) Driving of casing and advancing of boring by bailer should be done alternately to progress the cased borehole without endangering the adjacent stone column already installed.

f) At commencement of boring, a guide boring of 0.5 m to 1.0 m depth should be drilled with bailer in order to properly support the casing within the borehole to facilitate driving by bailer.

g) Sectional lengths of the casing are added on till the desired depth of treatment has been reached.

h) When the casing has reached the desired depth of the column, chemically inert, sound and well graded crushed rock of 75 mm down to 2 mm is placed in the casing to fill it to about 1 m to 1.5 m depth.

j) After placement of this charge, the casing is withdrawn making sure that its bottom invariably remains a minimum of 0.5 m into the aggregate.

k) The loose charge below the bottom of the casing is then compacted by operating a rammer of suitable weight and fall within the casing so as to obtain a ramming energy of around 20 KNm (Joules) per blow.

m) The extent of ramming is measured by the set criterion, that is, by measuring penetration of the rammer into the backfilled material or a given number of blows. For the rammer system proposed to be used, the set criterion would be established individually for each site by conducting appropriate field trials. Although the set will be governed by the rammer input energy as well as the fill characteristics, a satisfactory compaction is considered to be achieved when a set of 10 mm or less is obtained for the last 5 blows using rammer energy of the order mentioned in **C -1.1 (k)**.

n) It may be noted that the compaction of the granular fill depends upon the inter-related factors of the column, the soil, the rammer system, the installation procedure, etc. However, a heavier rammer is more effective for a given energy than a lighter rammer of comparable output energy.

p) Subsequent to achieving the desired compaction as in **C-1.1 (n)**, the next charge is placed in the casing and it is rammed in accordance with the **C-1.1 (k)** to **C-1.1 (m)**. The procedure is repeated till a stone column of the desired length has been formed.

C-1.2 Direct Mud Circulation (DMC) Method

In this method, the borehole walls may be stabilized with bentonite mud. However, prior to putting in the stone charge, a casing of suitable diameter is lowered to the bottom of the borehole, bentonite mud completely pumped out and the same is replaced with clean water. Backfilling of the hole with stone charges and their compaction in stages is done in the same manner as described in **C-1.1**.

NOTE — For formation of a stone column of an acceptable quality column of water in the excavated hole should be kept clear of suspended/settled impurities. Attempt should be made to achieve a high degree of clarity of water devoid of turbidity to the extent possible. This may be achieved by replacing the water in the hole at regular intervals.

C-1.3 Rotary Drill Method

In this method, boring is performed with rotary equipment employing augers or buckets. The borehole sides may be stabilized using a casing or alternatively, by using bentonite mud as per **C-1.2**. Driving of casing to stabilize the boreholes sides, pouring of stone charge and compaction of the same is done in the same manner as in **C-1.1** and **C-1.2**.

NOTE — In the boring methods prescribed in **C-1.1** to **C-1.3**, the following precautions should be taken:

i) Suction caused by bailer can induce ingress of soft/loose soil into the borehole from under the casing, even if the water level in the borehole is kept sufficiently above the ground water table. This action can cause damage to the neighbouring columns. To mitigate this problem, suitable size of the bailer should be selected as per **C-1.1** (d).

ii) Compaction of stones under water may require provision of a special hammer.

C-2 DISPLACEMENT METHOD

In this method, a closed end pipe mandrel is driven to the desired depth and the trip valve opened to discharge the stone in appropriate stages. Either an internal rammer packs the soil with stone through the pipe as is it withdrawn as further stone charge is added, or the mandrel is withdrawn until the valve can be closed and the entire mandrel with the valve in closed position is used to ram against the stone with a hammer operating over the mandrel to expand and density the column.

While installing a large group of stone columns, the sequence of installation should be from the centre to the periphery or one side to the other for avoiding possibility of damaging neighbouring columns and heaving of soil, particularly in stiff clay or compact sand layers.

C-3 VIBRO-REPLACEMENT METHOD

In this method, creation of hole in the ground and compaction of granular fill backfilled in the hole is accomplished mechanically using a vibratory unit called vibroflot. Stone columns may be constructed using this equipment either by:

a) *Wet process* — Generally suitable for soft to firm soil with high water table condition where borehole stability is questionable, or

b) *Dry process* — Suitable for soils of relatively high initial strength with relatively low water table where the hole can stand of its own upon extraction of the probe, such as unsaturated fills.

C-3.1 Vibroflot

C-3.1.1 Several versions of the vibroflot may be available with respect to its diameter, length and weight. Specialist opinion may be sought for an appropriate selection of the equipment after giving due consideration to the soil type, its strength characteristics, depth of treatment, etc. The following clauses give broad features of the vibroflot currently in use in India and the procedure for constructing the stone column in clays with strengths varying from 0.07 kg/cm^2 to 0.5 kg/cm^2. In ground with cohesion greater than 0.5 kg/cm^2, special version of the vibroflot may be used or alternatively, a non displacement method may be employed:

a) The vibroflot is a poker vibrator normally of diameter ranging from 300 mm to 450 mm and about 2 m to 3.5 m long. It weighs 2 t to 4 t depending upon the size.

b) A typical vibroflot probe is shown in Fig. 7. It consists of two parts:

   i) Vibrator, and
   ii) Follower pipes/tubes.

c) The vibrator contains eccentric weights mounted at the bottom on a vertical shaft directly linked to a motor in the body of the machine. Thus, the vibratory motion is horizontal with the body cycling around a vertical axis.

d) While the vibrator is in motion, the follow up pipe remains almost stationary. This is achieved by inserting a universal connection (vibration isolator) between the two parts. The follow on tube which has diameter somewhat less than that of the vibrator is provided in the form of extension pieces to allow deep penetration into the ground. The tube carries power/hydraulic oil lines and water pipes from the surface for jets in the nose cone and sides of the vibrator. Electric machines can be coupled to the local generator while the hydraulic machines generally have a power pack as a separate unit placed adjacent to the suspending crane.

e) The most common power development is in the range of 35 kW to 100 kW. Large machines which develop power upto 160 kW may also be used depending on subsoil conditions and the corresponding lateral impact forces may vary from 5 t to over 30 t.

f) Vibration frequencies usually are fixed either at 30 Hz or 50 Hz to suit electric power cycles. When hanging free, half amplitudes of the vibroflot are generally between 5 mm to 10 mm. However, when machine is working hard and restrained by the ground, they are somewhat less thereby limiting the lateral compaction depending upon the relative weights and positions of the moving and static parts as well as the power and speed of the machine and the subsoil conditions.

g) Other auxiliary equipments in addition to the accompanying power pack system include water pump, crane, welding set, etc. The water pump provides water under pressure to jet the vibroflot into the ground as it is lowered down by the crane.
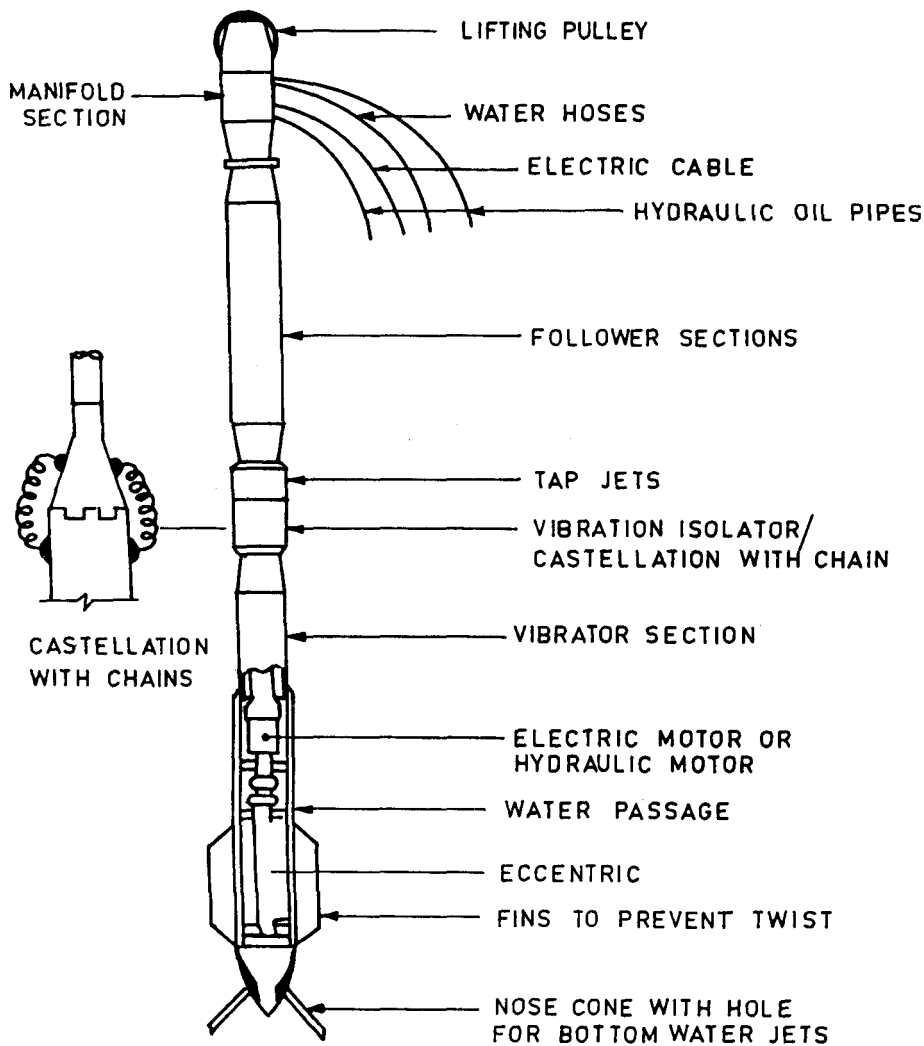
LIFTING PULLEY

MANIFOLD
SECTION

WATER HOSES

ELECTRIC CABLE

HYDRAULIC OIL PIPES

FOLLOWER SECTIONS

TAP JETS

VIBRATION ISOLATOR/
CASTELLATION WITH CHAIN

VIBRATOR SECTION

CASTELLATION
WITH CHAINS

ELECTRIC MOTOR OR
HYDRAULIC MOTOR

WATER PASSAGE

ECCENTRIC

FINS TO PREVENT TWIST

NOSE CONE WITH HOLE
FOR BOTTOM WATER JETS

FIG. 7 ESSENTIAL FEATURES OF VIBROFLOT

C-3.1.2 *Compaction Procedure*

a) Each compaction sequence begins with the probe freely suspended from the crane and set to vibrate. It simultaneously releases water from the lower jets which remove the soft soil directly under the vibroflot nose forming a hole. This operation allows practically an unimpeded penetration of the vibroflot into the soil under its own weight. No increase in density of the soil is achieved during this operation of the probe penetration.

b) When the vibroflot has reached the desired depth, the water supply to the lower jet is reduced suitably and the top jets are put on. Wash water from these upper jets returns to the ground surface through the annulus between the outside of the follow on tubes and the crater sides. This upward flow maintains an open channel along the sides of the vibroflot permitting backfill material shoved from the surface to reach the bottom and it also prevents the probe from sticking. The annular wash water flow is established by raising (surging) the vibroflot twice or thrice to clean the loose soft soils from the hole. When the water flow continuously returns to the surface, the probe is raised by suitable lift, say 1.5 m and the backfill is poured into the annular space between the poker and the side walls of the hole. The horizontal vibrations generated by the poker drive the stones laterally into the soil to form a column of an enlarged diameter. Combination of bottom and top water jets may also be used depending upon the soil condition during boring and compaction.

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c) Care must be taken during construction for not allowing the side walls of the hole to collapse and foul the stones. This is avoided by keeping the water flowing throughout construction to help stabilize the hole side walls.

d) Stone is generally placed in lifts of appropriate thickness.

e) The power of the unit should be selected based on the strength of the soil to be treated as well as the density of the stone backfill to be achieved. Vibroflots with 30 hp to 120 hp motor are generally in use in India depending upon the initial shear strength of the soil. The power input of the motor is measured by a recording ammeter/pressure gauge. The power input remains relatively constant during the insertion operation. However, as compaction of the granular fill proceeds, the resistance to movement around the vibroflot unit increases requiring a greater power input. When the maximum input, that is, the rated power of the machine is reached, the ammeter/pressure peaks indicating achievement of the maximum density of the backfill. Thus, ammeter/ hydraulic pressure provides a means to control the compaction level of the granular fill in the field. The next lift of the stone backfill is lodged in and the compaction cycle is repeated.

f) When the upward flow of wash water is pinched off due to the hole collapse during extraction, it may be regained by repeated raising and plunging of the vibroflot (surging).

g) The penetration rate of vibroflot into the ground during the insertion varies depending upon the flow rate and pressure of water and soil conditions.

C- 3.1.3 *Factors Influencing Vibrofloted Stone Columns*

a) In addition to the equipment factors stated above, the other factors influencing installation of stone columns by vibroflot include soil type, initial soil strength, probe spacing and pattern. Spacing and volume replacement is highly site specific.

b) For soils containing more than 20 percent fines (less than 0.074 mm size), stone columning may be adopted for improving the engineering properties of the soil. The soft clays to be treated should have their sensitivity not exceeding 4, preferably 3 and under and undrained shear strength generally not less than 0.7 t/m².

NOTE — Sensitivity is also important for columns installed by non-displacement technique and are subject to the same limits as above and it should also be checked by laboratory tests.

c) Crushed stone or gravel may be used as backfill material. The individual stones should be chemically inert, hard and resistant to breakage. The size of material should not be too large to cause arching of stones between the vibroflot and the borehole walls thereby preventing the material to reach the tip of the vibrator. Well graded stones of 75 mm to 2 mm size may be used. It may be noted that stones of uniform size may permit penetration of clay into the large sized voids thereby jeopardizing the capacity of the column and/or its function as a vertical drain. Backfill gradation, rate of shoving the backfill material into the hole and the upward water velocity should be carefully controlled during the backfilling operation as they have significant effect on the backfill densities achieved.

d) The personnel operating the machine should be experienced enough to be able to quickly identify the situations, such as premature quitting of shoving bookfill material into the crater, caving of hole due to inadequate water pressure resulting in pinching of the channel along the sides of the vibroflot, extracting probe at too fast a rate, excessive washwater velocity and take remedial measures so as not to allow the vibroflot to starve of the backfill at any stage of the compaction process.

ANNEX D

(*Clause* 14.2)

TYPICAL DATA SHEET FOR RECORDING INSTALLATION OF STONE COLUMNS

NAME OF AGENCY:

STONE COLUMN INSTALLATION RECORD

Name of work: Name of client:

Drawing No.:   Date/Shift:

Sl No. :	Time of start of boring:
Location :	Time of end of boring:
Diameter :	Time of start and finish of compaction of each batch of stones:
Actual ground level :	
Length of tube :	Total time taken for compaction of all batches of stones:
Type of hammer :	Total time taken for installation of stone column:
Weight of hammer :	
Stroke/Drop of hammer :	Length of stone column from GL:
Total No. of blows :	Total volume of stones consumed:
Set for last 5 blows :	
Repeat set for 5 blows :	

ANNEX E

(Foreword)

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