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व्यापक परिचालन मसौदा

हमारा संदर्भ : सीईडी 43/टी-124 **23 दिसम्बर 2023**

तकनीकी समिति : मृदा एवं नींव इंजीनियरी विषय समिति, सीईडी 43

प्राप्तकर्ता :

1 सिविल इंजीनियरी विभाग परिषद, सीईडीसी के सभी सदस्य
2 मृदा एवं नींव इंजीनियरी विषय समिति, सीईडी 43 के सभी सदस्य
3 आईएस 15284 (भाग 1 और 2) के पुनरीक्षण के लिए पैनल, सीईडी 43:पी16 के सभी सदस्य
4 रूचि रखने वाले अन्य निकाय।

महोदया/महोदय,

निम्नलिखित मसौदा संलग्न है:

प्रलेख संख्या	**शीर्षक**
सीईडी 43 (24470)WC	**भूमि सुधार के लिए डिजाइन और संरचना – रीति संहिता : भाग 1 पाषाण स्तंभ का भारतीय मानक मसौदा [IS 15284 (भाग 1) *का पहला पुनरीक्षण*]** **(ICS No. 93. 020)**

कृपया इस मसौदे का अवलोकन करें और अपनी सम्मतियाँ यह बताते हुए भेजे कि यह मसौदा प्रकाशित हो तो इस पर अमल करने में, आपको व्यवसाय अथवा कारोबार में क्या कठिनाइयाँ आ सकती हैं।

सम्मतियाँ भेजने की अंतिम तिथि: 31 जनवरी 2024

सम्मति यदि कोई हो तो कृपया अधोहस्ताक्षरी को ई मेल द्वारा **madhurima@bis.gov.in** पर या उपरलिखित पते पर, संलग्न फोर्मेट में भेजें।

यदि कोई सम्मति प्राप्त नहीं होती है अथवा सम्मति में केवल भाषा संबंधी त्रुटि हुई तो उपरोक्त प्रलेख को यथावत अंतिम रूप दे दिया जाएगा। यदि सम्मति तकनीकी प्रकृति की हुई तो विषय समिति के अध्यक्ष के परामर्श से अथवा उनकी इच्छा पर आगे की कार्यवाही के लिए विषय समिति को भेजे जाने के बाद प्रलेख को अंतिम रूप दे दिया जाएगा।

यह प्रलेख भारतीय मानक ब्यूरो की वैबसाइट **www.bis.gov.in** पर भी उपलब्ध हैं।

धन्यवाद।

भवदीय
ह/-
(अरुण कुमार एस.)
वै. 'ई'/निदेशक और प्रमुख (सिविल इंजीनियरी)

सलंग्न: उपरिलिखित

भारतीय मानक ब्यूरो
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DOCUMENT DESPATCH ADVICE

Reference	Date
CED 43/T-124	23 December 2023

TECHNICAL COMMITTEE:

SOIL AND FOUNDATION ENGINEERING SECTIONAL COMMITTEE, CED 43

ADDRESSED TO:

1. All Members of Civil Engineering Division Council, CEDC
2. All Members of Soil and Foundation Engineering Sectional Committee, CED 43
3. All Members of Panel for Revision of IS 15284 (Parts 1 and 2), CED 43:P16
4. All other interests

Dear Madam/Sir,

Please find enclosed the following draft:

Doc. No.	Title
CED 43 (24470)WC	**Draft Indian Standard Design and Construction for Ground Improvement — Code of Practice : Part 1 Stone Columns [*First Revision of* IS 15284 (Part 1)]** **(ICS No. 93.020)**

Kindly examine the draft and forward your views stating any difficulties which you are likely to experience in your business or profession, if this is finally adopted as National Standard.

Last Date for comments: 31 January 2024

Comments if any, may please be made in the enclosed format and emailed at **madhurima@bis.gov.in** or sent at the above address.

In case no comments are received or comments received are of editorial nature, you will kindly permit us to presume your approval for the above document as finalized. However, in case comments, technical in nature are received, then it may be finalized either in consultation with the Chairman, Sectional Committee or referred to the Sectional Committee for further necessary action if so desired by the Chairman, Sectional Committee.

The document is also hosted on BIS website **www.bis.gov.in**.

Thanking you,

Yours faithfully,
Sd/-
(Arun Kumar S.)
Sc. 'E'/Director and Head (Civil Engg.)

Encl: As above

FORMAT FOR SENDING COMMENTS ON BIS DOCUMENTS

(Please use A4 size sheet of paper only and type within fields indicated. Comments on each clause/subclause/table/fig etc. be started on a fresh box. Information in column 5 should include reasons for the comments, and those in column 4 should include suggestions for modified wording of the clauses when the existing text is found not acceptable. Adherence to this format facilitates Secretariat's work) {Please e-mail your comments to madhurima@bis.gov.in }

DOC. NO.	**Doc: CED 43 (24470)WC**
TITLE	**Draft Indian Standard Design and Construction for Ground Improvement — Code of Practice : Part 1 Stone Columns [*First Revision of* IS 15284 (Part 1)]** **(ICS No. 93.020)**
LAST DATE OF COMMENTS	**31 January 2024**
NAME OF THE COMMENTATOR/ ORGANIZATION	______________________________

Sl No. (1)	**Clause/Sub-clause/Para No. (2)**	**Comments/Suggestions (3)**	**Modified Wording of the Clause (4)**	**Reasons/ Justifications for the Proposed Changes (5)**

DOC: CED 43 (24470)WC
December 2023

BUREAU OF INDIAN STANDARDS

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Draft Indian Standard

DESIGN AND CONSTRUCTION FOR GROUND IMPROVEMENT — CODE OF PRACTICE

PART 1 STONE COLUMNS

(*First Revision*)

Soil and Foundation Engineering Sectional Committee, CED 43	Last Date for Comments: **31 January 2024**

FOREWORD

(*Formal clauses to be added later*)

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 having wide spread loads which include steel storage tanks, embankments, fills, industrial structures, port facilities, treatment plants, power plants, infrastructure projects including airports, residential and commercial structures, etc.

Several ground treatment techniques are available which may meet the objective of increasing the bearing capacity with simultaneous reduction of settlements, mitigating liquefaction potential and improving stability of slopes. Reinforcing the ground using stone columns is one of such techniques. The country presently has the experience of improving ground using this technique up to the depth of 35.0 m.

This standard (Part 1) was published in 2003 as a guideline standard to cover design and construction for ground improvement using stone columns. It has been felt that the provisions regarding stone columns should be further revised to take into account the recent developments in this field. This revision has been brought out to incorporate these developments.

In this revision of the standard, the following major modifications have been made:

a) The standard was previously brought out as a guideline standard as the experience of ground improvement techniques in the country was limited. With lot of experience gained over the years, it has been decided to bring out the revised standard as a code of practice standard. The title of the standard has been changed accordingly.
b) Definitions of various terms have been modified as per the prevailing engineering practice.
c) Areas of application of stone columns have been modified.
d) Alternative design methodology using Priebe method has been incorporated.
e) Consolidation settlement analysis has been incorporated.
f) Liquefaction analysis after installation of stone columns has been incorporated.
g) Provisions on installation of stone columns have been modified based on the current practices.
h) The frequency of routine load test has been reduced.

The Part 2 of the standard, namely IS 15284 (Part 2):XXXX 'Design and construction for ground improvement — Code of practice: Part 2 Pre-consolidation using vertical drains (*first revision*)' covers ground improvement using vertical drains.

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 : 2022 'Rules for rounding off numerical values (*second revision*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

DOC: CED 43 (24470)WC
December 2023

BUREAU OF INDIAN STANDARDS

DRAFT FOR COMMENTS ONLY

Draft Indian Standard

DESIGN AND CONSTRUCTION FOR GROUND IMPROVEMENT — CODE OF PRACTICE

PART 1 STONE COLUMNS

(*First Revision*)

Soil and Foundation Engineering Sectional Committee, CED 43	Last Date for Comments: **31 January 2024**

1 SCOPE

1.1 This standard (Part 1) covers the design methodology as well as the construction techniques for installation of stone columns. The scope is limited to the computation of allowable loads and settlements for wide spread loads.

1.1.1 Stone columns may be adopted for improving the engineering properties of the soils containing fines more than 15 percent passing through 0.075 mm sieve.

1.1.2 This ground improvement technique is used to,

a) improve bearing capacity;
b) improve stability of slopes;
c) reduce settlements;
d) accelerate consolidation process in saturated conditions; and
e) mitigate liquefaction potential, if any.

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*
IS 383 : 2016	Coarse and fine aggregate for concrete — Specification (*third revision*)
IS 1892 : 2021	Subsurface investigations for foundations — Code of practice (*second revision*)
IS 1893 (Part 1) : 2016	Criteria for earthquake resistant design of structures: Part 1 General provisions and buildings (*sixth revision*)
IS 6403 : 1981	Code of practice for determination of bearing capacity of shallow foundations (*first revision*)
IS 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 Ground Improvement — To improve the shear strength or compressibility characteristics of the loose or soft soil to the required depth by some practical methods.

3.2 Sensitivity of Clay — The ratio of the unconfined compressive strength of an undisturbed specimen of the soil to the unconfined compressive strength of specimen of the same soil after remoulding at unaltered water content.

3.3 Displacement Type of Installation Process — Installation process in which the soil is laterally displaced while making the hole due to driving of a tube or a casing or a vibrator probe.

3.4 Non-displacement Type of Installation Process — Installation process in which the soil is taken out during boring process.

NOTE — This method is also known as replacement method.

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

3.6 Initial Test Stone Column — Stone columns, which are not working stone columns, but are installed for assessing the load carrying capacity of the improved ground.

3.7 Initial Load Test — The test intended to be conducted on initial test stone column(s) at initial stage of project to assess the load carrying capacity of the improved ground. Such column(s) shall be tested either to its ultimate load capacity or to at least 1.5 times the working load.

3.8 Routine Test Stone Column — The working stone column that is selected for carrying out load testing. These columns shall be tested to 1.1 times of the design load.

3.9 Routine Load Test — Test carried out on a working stone column(s) with a view to check whether the improved ground is capable of taking the working load assigned to it without exceeding permissible settlement.

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

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

3.12 Factor of Safety — It is the ratio of the ultimate load capacity of a stone column to the safe load carrying capacity of the stone column.

3.13 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.

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

4 NECESSARY INFORMATION

For the satisfactory design and installation of stone columns, the following information shall be required:

a) Sub-surface investigation data as laid down in IS 1892 including any other relevant Indian Standard, as applicable for specific projects. Borelogs should be supplemented by penetration tests and other in-situ test results up to the required depth as per IS 1892.

b) Ground water level and its seasonal fluctuations.

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

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 equipment 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 GENERAL ASPECTS OF STONE COLUMN TREATMENT

6.1 Influence of Soil Type

The very soft clay soil (silty clay/sandy clay) whose undrained shear strength is more than 7 kPa or loose sandy soils including silty or clayey sands represent a potential class of soils requiring improvement by stone columns. In case of very soft clay having undrained shear strength less than 7 kPa, where stone column formation may be doubtful, the ground improvement may be resorted to geogrid wrapped/encased stone columns with proven track records using specialist design and execution. Caution shall be exercised when adopting stone columns for sensitive clays and silts (sensitivity ≥ 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 inadequate bearing or liquefaction potential or slope failure.

6.4 Area of Stone Column Application

Stone columns are more viable for large area stabilization of the soil mass. Large loaded areas which apply uniform loading on foundation soils, such as beneath embankments, tank farms, fills, industrial structures, port infrastructure facilities, treatment plants, power plants, other infrastructure projects including airports, residential and commercial structures represent a major area of application.

6.5 Termination

End bearing is not a specific requirement for stone columns. However, they should extend through the soft compressible strata and terminated in competent soil strata (stiff clay layers/medium dense sand layer) or as per the design requirements.

6.6 Column Materials

6.6.1 Granular material such as crushed stone aggregate/crushed pebbles/crushed concrete/coarse sand (Zone I and Zone II as per IS 383) may be used as a backfill material for the construction of columns. The granular material shall be chemically inert, hard and resistant to breakage. The size of material should not be too large to cause blocking of holes by stones between the vibroflot and the borehole walls or inside the stone tube thereby preventing the material to reach the tip of the vibrator. The material sizes shall be followed as per the following:

a) Displacement method : 8 mm to 50 mm; and
b) Non-Displacement/Replacement method : 12 mm to 100 mm.

6.6.2 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.

7 BASIC DESIGN PARAMETERS

7.1 Stone Column Diameter, *D*

7.1.1 Installation of stone columns in soft cohesive soils/loose sandy soils is basically a self-compensating process, that is, weaker 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 stone column is always greater than the initial diameter of the probe or the casing depending upon the soil type, initial shear strength of the soil, 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.

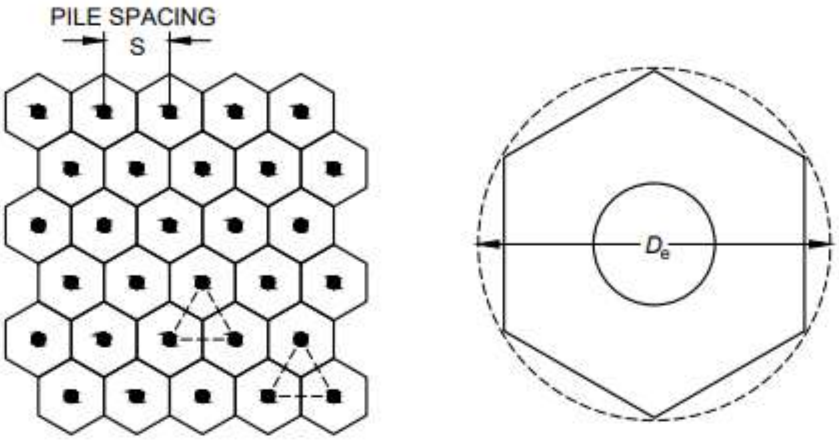
7.2 Pattern

Stone columns shall be installed in an equilateral triangular pattern or square pattern. A typical layout of an equilateral triangular pattern and square pattern is shown in Fig. 1.

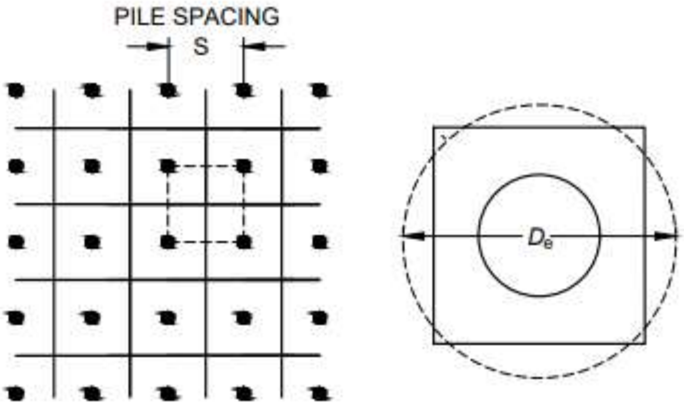
7.3 Spacing

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 1.5 D to 3 D depending upon the site conditions, loading and its distribution, the installation technique, settlement tolerances, etc.

7.3.1.1 For large projects, it is desirable to carry out field trials to determine the most optimum spacing of stone columns taking into consideration the project specific requirements such as the required bearing capacity of the soil, permissible settlement of the foundation, liquefaction resistance and lateral deformations.



1A TRIANGULAR ARRANGEMENT OF STONE COLUMNS



1B SQUARE ARRANGEMENT OF STONE COLUMNS

FIG. 1 VARIOUS PATTERNS OF STONE COLUMNS

7.4 Equivalent Diameter

7.4.1 The tributary area of the soil surrounding each stone column forms regular hexagon or square around the column for equilateral triangular and square pattern, respectively. It may be closely approximated by an equivalent circular area having the same total tributary area (*see* Fig. 1).

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

D_e = 1.05 S for an equilateral triangular pattern, and
= 1.13 S for a square pattern.

where

S = spacing of the stone columns.

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

7.5 Area Replacement Ratio (a_s)

7.5.1 For the purpose of analysis, the composite ground representing an infinitely wide loaded area may be modeled as a unit cell comprising the stone column and surrounding soil in the tributary area. To quantify the amount of soil replaced by the stone, the term area replacement ratio, a_s is used, which is given by the following equation:

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

where

A_s = area of the stone column;
A_g = area of ground surrounding the column in the tributary area; and
A = total area within the unit cell.

The area replacement ratio as per the above equation may also be expressed as follows:

For equilateral triangular pattern:

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

For square pattern:

$$a_s = 0.783\ (D/S)^2$$

where

D = diameter of the stone column; and
S = spacing between the stone columns.

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 the average stress on the stone column, σ_s, to the stress, σ_g, on the soil surface within the unit cell,

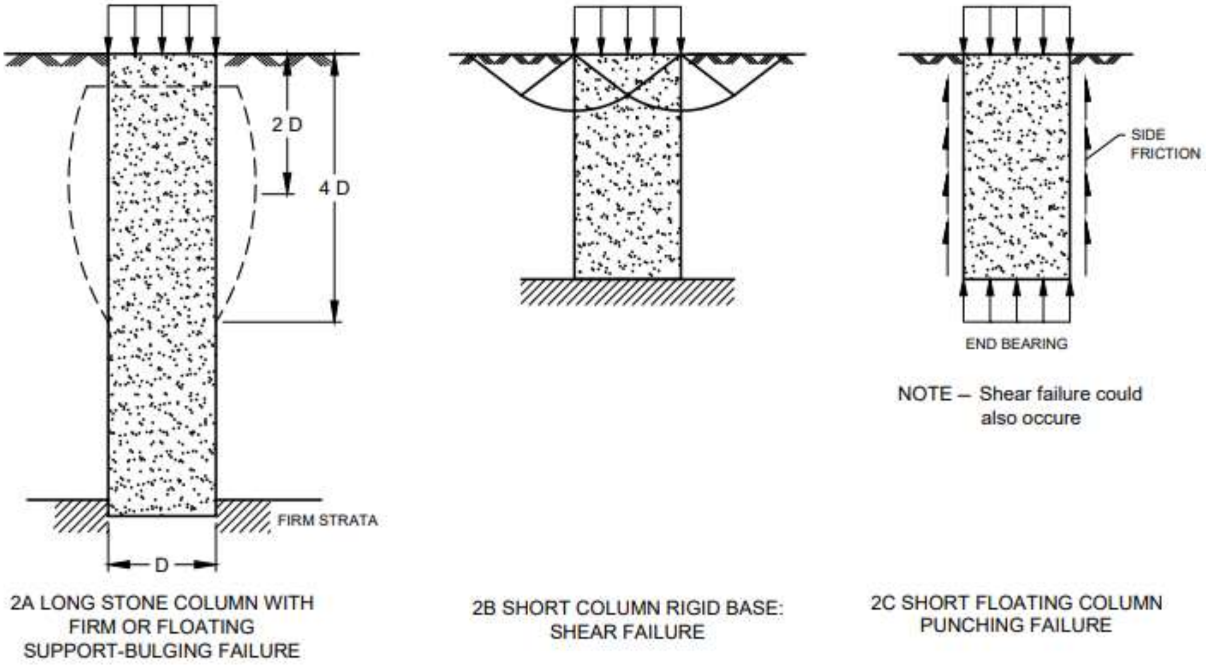
$$n = \frac{\sigma_s}{\sigma_g}$$

The value of n generally lies between 2.5 and 5 at the ground surface. The stress concentration factor (n) decreases with time of consolidation and also 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 soil 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. 2A). 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 (*see* Fig. 2C).



NOTE — Shear failure could also occure

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

2B SHORT COLUMN RIGID BASE: SHEAR FAILURE

2C SHORT FLOATING COLUMN PUNCHING FAILURE

FIG. 2 FAILURE MECHANISMS OF A SINGLE STONE COLUMN IN A HOMOGENOUS SOFT LAYER

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.

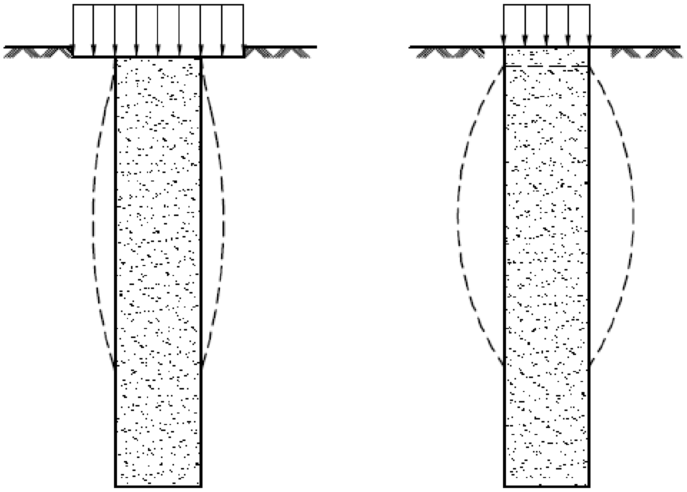


FIG. 3 DIFFERENT TYPE OF LOADING APPLIED TO STONE COLUMNS

8.2.1 The above failure mechanism 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.

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

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, should be determined from the following equation:

$$\frac{\sigma_1}{\sigma_3} = \frac{1 + \sin \emptyset_s}{1 - \sin \emptyset_s}$$

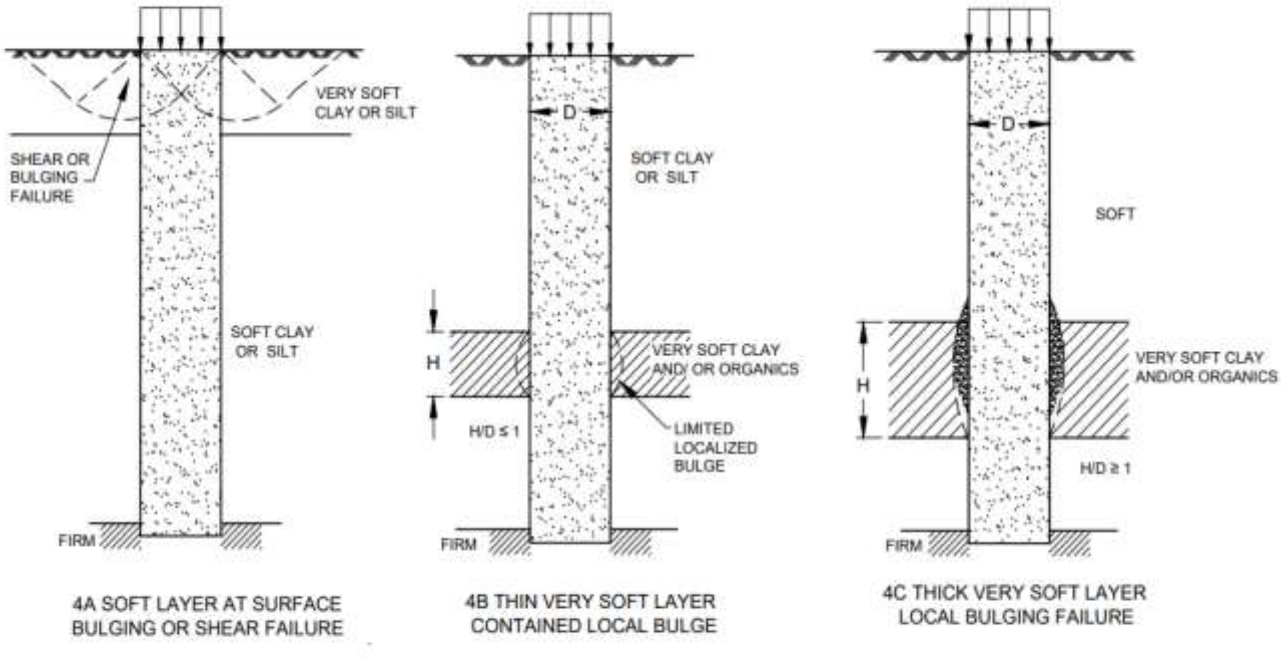
where

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



4A SOFT LAYER AT SURFACE BULGING OR SHEAR FAILURE

4B THIN VERY SOFT LAYER CONTAINED LOCAL BULGE

4C THICK VERY SOFT LAYER LOCAL BULGING FAILURE

FIG. 4 STONE COLUMN FAILURE MECHANISMS IN NON-HOMOGENOUS COHESIVE SOIL

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 Estimation of Ultimate Load Carrying Capacity and Settlement

The ultimate load carrying capacity and settlement of stone column under working loads should be estimated on the basis of soil investigation data obtained as per IS 1892. The procedures given in Annex A and Annex B should be used for estimating the ultimate load carrying capacity and settlement of a single column/group of columns under the working load, respectively.

9.4 Liquefaction Resistance of Stone Colum Improved Ground

Stone columns are also used to improve liquefaction prone soil deposits. Liquefaction potential of improved ground treated with stone columns shall be determined in accordance with Annex C.

9.4.1 *Confinement Rows*

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 or for the liquefaction mitigation. 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. In general practice, minimum one confinement row should be provided outside the footprint area or based on the requirements and in case of liquefaction mitigation, the extent of treatment should be half of the liquefaction depth including any non-liquefiable layers in between the liquefiable layers (*see* Fig. 5).

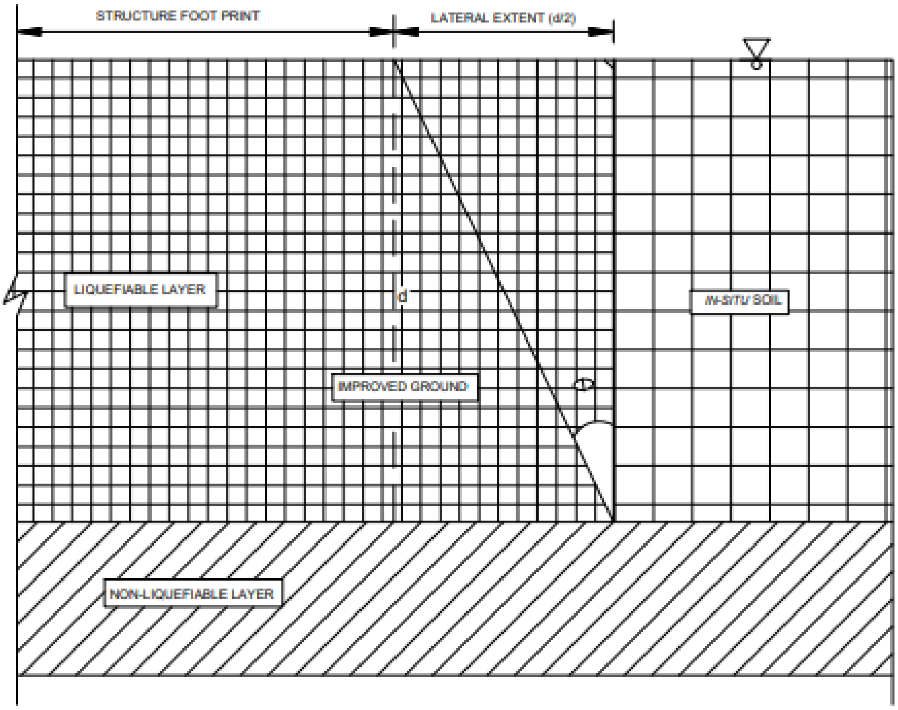


FIG. 5 TREATMENT AREA - LATERAL EXTENT

9.5 Environmental Factors

Design considerations should take into account the environmental factors, such as presence of aggressive chemicals in the sub-soil and ground water and artesian conditions.

9.6 Load Test Results

Ultimate load carrying capacity shall be determined by an initial load test on a test column(s) specifically installed for the purpose and tested to its ultimate load carrying capacity in accordance with **13**. The settlement of a stone column obtained at safe/working load from load test results on a single column shall not be directly used in forecasting the settlement of the structure.

9.7 Factor of Safety

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

a) Nature and variability of the sub-strata;
b) Reliability of the value of ultimate load carrying capacity of the stone column;
c) Type of superstructure and the type of loading; and
d) Manner of load transfer from stone column to the soil.

9.7.2 When ultimate capacity is derived in accordance with Annex A, the minimum factor of safety shall be 2.5.

10 INSTALLATION TECHNIQUES

The stone columns should be installed using any of the following construction techniques as described in Annex D:

a) Non-Displacement Method

  i) Bailer and casing method;
  ii) Rotary drill method; and
  iii) Deep vibro techniques using wet top feed method.

b) Displacement Method

  i) Deep vibro techniques using dry bottom feed method; and
  ii) Rammed stone columns.

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 shall be sand/crushed stone aggregate/crushed stone aggregate and sand mix, based on the project requirements. The granular blanket material should be permeable and shall be laid in thin layers, and every layer should be compacted with vibratory rollers to achieve minimum relative density of 70 percent.

11.2 In general minimum thickness of the compacted granular blanket should be 0.5 m. In case of combination of stone columns and pile foundation to mitigate liquefaction, the minimum thickness of granular blanket should be 0.3 m. This blanket should be exposed to atmosphere at its periphery for pore water pressure dissipation.

11.3 Stone columns shall be exposed after ensuring complete removal of slush deposited during installation prior to laying of granular blanket. The exposed surface shall be levelled and compacted by other suitable means, such as rolling/tamping to the specified densification criteria. Granular blanket shall be laid over the levelled ground in accordance with **11.1** and **11.2**.

11.4 Basal reinforcement using geogrid/geosynthetic material may also be used as a load distribution layer. This layer can be provided in between the granular blanket layers or between stone columns and blanket. The basal reinforcement shall be designed by the expert as per the project requirements.

12 FIELD CONTROLS

12.1 In the methods involving boring, 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 should be established as per **D-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 during the installation process.

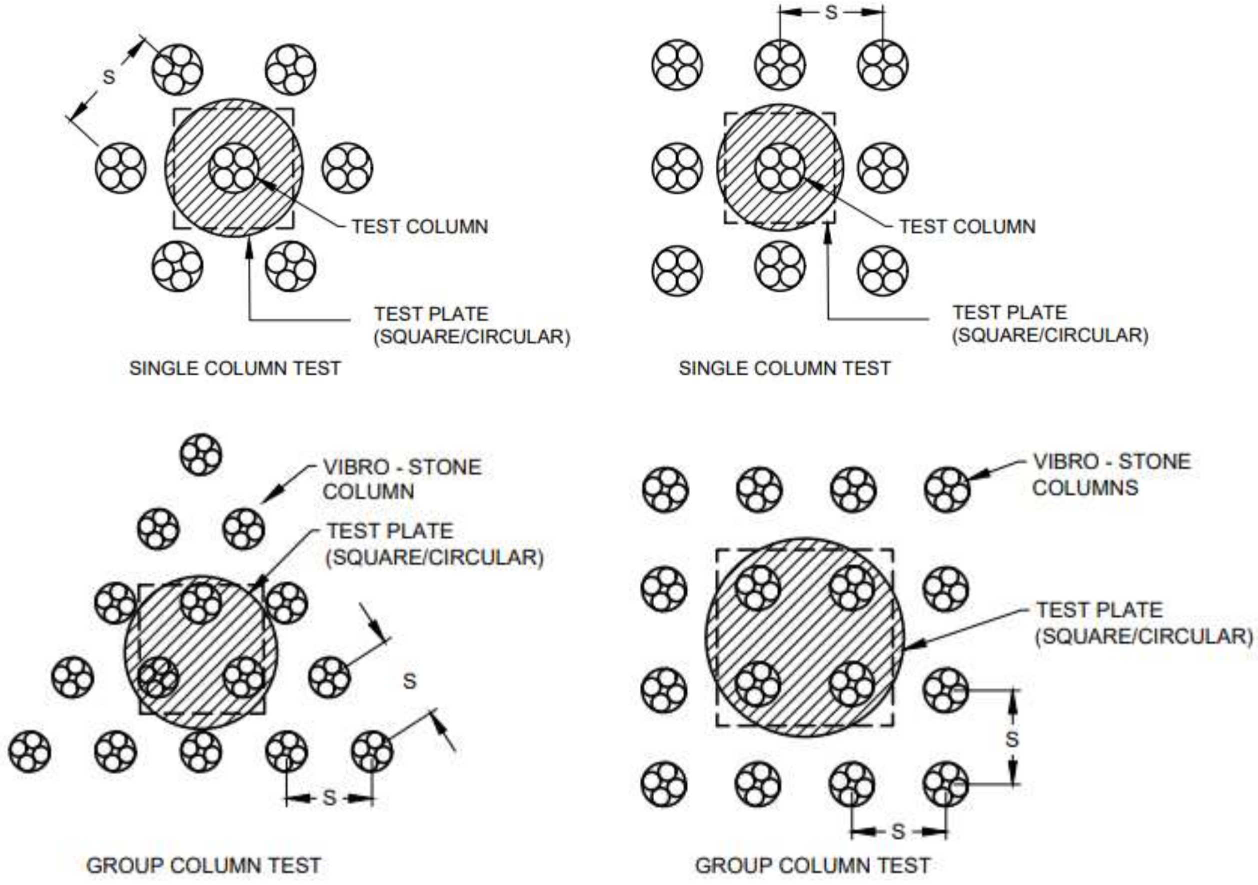
13 FIELD LOAD TESTS

13.1 The initial load tests shall be performed at the same site where stone columns are to be constructed. The test should be conducted on initial test column to evaluate the load-settlement behaviour of the soil-stone column system. Initial test columns should be installed by the selected technique and type of equipment as that proposed for working columns. The tests should be conducted on a single and also on a group of minimum three columns for equilateral triangular pattern and minimum four columns for square pattern.

13.2 For the initial load tests, in order to simulate the field conditions of compaction of the intervening soil, the minimum number of columns shall be installed as per the details given below:

Sl No.	*Pattern*	*Minimum Number of Columns to be Constructed for Initial Load Test*	
		For Single Column Test	*For Group Column Test*
(1)	(2)	(3)	(4)
i)	Equilateral triangular	7	15
ii)	Square	9	16

The typical arrangements of stone columns in triangular and square pattern for initial single column load test as well as the initial group column are shown in Fig. 6.



6A EQUILATERAL TRIANGULAR PATTERN 6B SQUARE PATTERN

FIG. 6 ARRANGEMENT OF STONE COLUMNS FOR INITIAL SINGLE AND GROUP LOAD TESTS

13.3 The size of the concrete footing or equivalent steel plate(s) of adequate thickness and rigidity shall be used for conducting the tests. The size of footing or plate shall be equivalent tributary area (*see* **7.4**) of stone column for a single column load test and three times the effective area of single column for a three-column group column load test. In each case, the footing may cover the equivalent circular effective area centrally.

13.4 The initial soil conditions at the site should be investigated by drilling at least one borehole or conducting a pressure meter test or a cone penetration test with pore water measurement (CPTu) for cohesive deposits prior to the column installation. All these tests including the standard penetration test or field vane shear tests (clayey soils) and collection of undisturbed/disturbed samples and laboratory testing on the samples shall be as per the relevant Indian Standards.

13.5 A granular blanket of medium to coarse sand having thickness not less than 500 mm shall be laid over the test column(s) as per **11**. A properly designed footing shall be laid over the blanket as explained in **13.3**.

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 shall be followed for application of load:

a) The load shall be applied to the footing by a suitable kentledge (*see* Fig. 7), avoiding impact, fluctuations or eccentricity.
b) The weight of the kentledge shall be minimum 1.25 times the maximum test load.
c) The initial test column(s) shall be tested to minimum load of 1.5 times the design load. Each stage of loading should be near about 1/5th of the design load. Each stage of loading shall be maintained till the rate of movement of the loading plate is not more than 0.2 mm/h or until 2 h have elapsed, whichever is earlier subject to a minimum of 1 h. The maximum test load shall be maintained for minimum 12 h after stabilization of settlement equal to or less than the rate as given above. The load cells may be used for measuring the load.
d) Settlements shall be recorded with minimum 4 dial gauges of 0.01 mm sensitivity for both single column and groups. The dial gauges shall be placed symmetrically and at equal distances from the column(s) and normally held by datum bars resting on immovable supports at a distance of 3D (subject to minimum of 2.0 m) from the edge of the test plate, where D is the size of the test plate., It is preferable to use remotely controlled linear variable differential transducers (LVDT) with a digital read out for recording the settlement from safety point of view and to minimize the disturbance to datum bars.
e) 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, 1/2 h, 1 h, 1-1/2 h, 2 h, 3 h, 4 h, and so on till the desired rate of settlement has been achieved.
f) The test load should be unloaded in five equal stages. At each stage, enough time should be allowed for settlements to stabilize.
g) The load test shall be considered acceptable if it meets the following settlement criteria:

    1) 12 mm settlement at design load for a single column test; and
    2) 30 mm settlement at the design load for a three column/four column group test.

h) Routine load test shall be conducted up to a minimum of 1.1 times the design load with minimum kentledge of 1.25 times the maximum test load. The testing frequency, for routine load tests should be:

    i) 1 routine single column test per 500 numbers of columns or part thereof;
    ii) 1 routine group column load test per 1 000 numbers of columns.

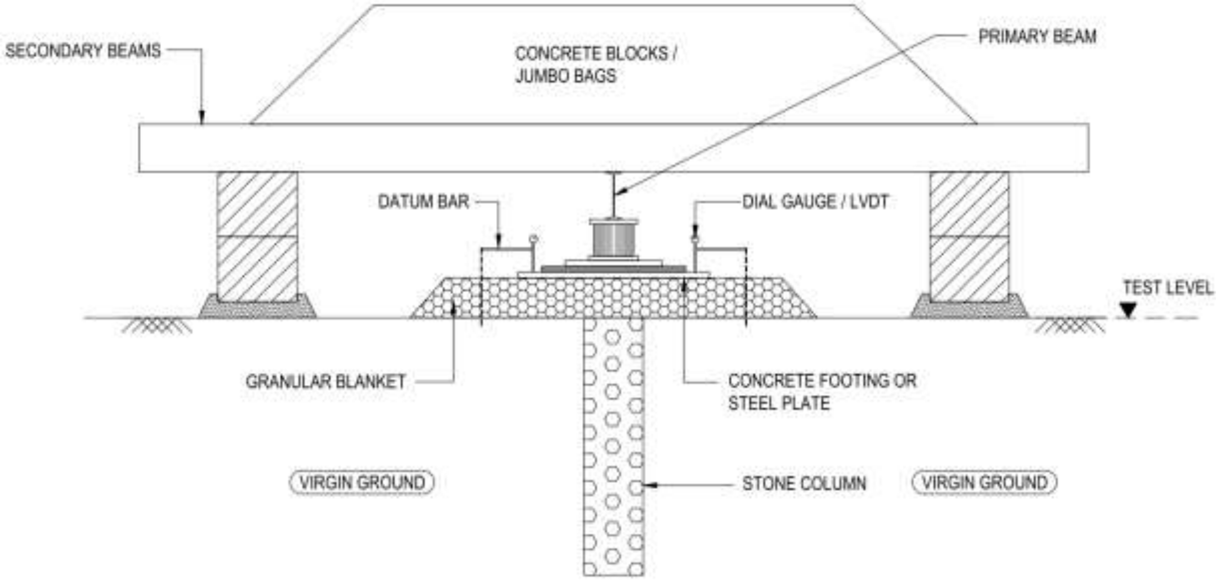


FIG. 7 TYPICAL ARRANGEMENT FOR A SINGLE COLUMN TEST

14 QUALITY CONTROL

14.1 The suitable quality control procedure shall be established for supervision and monitoring of stone column execution. The stone column design parameters (design diameter, depth and spacing) shall be verified at site. For monitoring each stone column, it is preferred to use automated computerized recording device which should provide the following minimum data:

a) Stone column reference number;
b) Date of installation;
c) Start and finish time of installation;
d) Duration of installation;
e) Installed depth; and
f) Compaction efforts during penetration and compaction process.

15 RECORDING OF DATA

15.1 A competent inspector should be appointed at site to record necessary information during installation of stone columns. All field installation data should be recorded but not limited to:

a) Method of installation of stone column;
b) Type of equipment used for installation of column along with the details of their size and capacity;
c) Sequence of installation of stone columns in a group;
d) Spacing of stone columns;
e) Dimensions of the stone column;
f) Depth of installation;
g) Record of actual consumption of stone for building columns which shall be meeting the requirements of theoretical design volume plus compaction efforts as per soil conditions and as per field trials;
h) Time taken for completing each stone column including withdrawal of casing, if any; and
j) Any other important observation during installation and after withdrawal of casing tube, if any.

15.2 Typical data sheet for recording stone column data is given in Annex E.

ANNEX A

(*Clauses* 9.3 *and* 9.7.2)

ESTIMATION OF ULTIMATE LOAD CARRYING CAPACITY OF A STONE COLUMN

A-1 STONE COLUMNS IN COHESIVE SOILS

Load carrying capacity of the treated ground should be obtained by summing up the contribution of each of the following components for wider and larger load applications:

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 following formula:

$$\sigma_{\mathrm{v}} = \sigma_{\mathrm{rL}}\, Kp_{\mathrm{col}}$$

$$\sigma_{\mathrm{v}} = (\sigma_{\mathrm{ro}} + 4C_{\mathrm{u}})\, Kp_{\mathrm{col}} \quad \text{... (1)}$$

where

σ_{v} = limiting axial stress in the column when it approaches shear failure due to bulging, and

σ_{rL} = limiting radial stress
= $\sigma_{\mathrm{ro}} + 4C_{\mathrm{u}}$

where

C_{u} = undisturbed undrained shear strength of clay surrounding the Column; and

σ_{ro} = initial effective radial stress
= $K_{\mathrm{o}}\sigma_{\mathrm{ro}}$

where

K_{o} = average coefficient of lateral earth pressure for clays equal to 0.6 or alternatively, as determined from the relationship, $\mathrm{K_o} = 1 - \sin \emptyset$, where $\emptyset$ 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 $\sigma_{\mathrm{vo}} = \gamma\ 2\mathrm{D}$

where

γ = effective unit weight of soil within the influence zone; and

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

where

$\emptyset_{\mathrm{c}}$ = 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 $\emptyset_{\mathrm{c}}$ may range from 38° to 42° depending upon the compactness achieved during construction of stone columns.

Yield load = $\sigma_{\mathrm{v}}\pi/4\, D^2$

Safe load on column alone, $Q_1 = \frac{Yield\ load}{Factor\ of\ safety} = \frac{\sigma_{\mathrm{v}}\pi/4\, D^2}{2}$ … (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:

$$\Delta\sigma_{\mathrm{ro}} = \frac{q_{\mathrm{safe}}}{3}(1 + 2\,K_{\mathrm{o}}) \qquad \dots (3)$$

where $\Delta\sigma_{\mathrm{ro}}$ 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 on ultimate bearing pressure obtained as per IS 6403.

$$q_{\mathrm{safe}} = C_{\mathrm{u}}N_{\mathrm{c}}/2.5$$

Increase in ultimate cavity expansion stress = $\Delta\sigma_{\mathrm{ro}} F_{\mathrm{q}}$'

Thus, increase in yield stress of the column = $Kp_{\mathrm{col}} \Delta\sigma_{\mathrm{ro}}\ F_{\mathrm{q}}$'

where

F_{q}' = vesic's dimensionless cylindrical cavity expansion factor

F_{q}' = 1 for $\emptyset_{\mathrm{g}} = 0$

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

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

$$Q_2 = \frac{Kp_{\mathrm{col}} \Delta\sigma_{\mathrm{ro}} A_s}{2} . F_q' \qquad \text{…(4)}$$

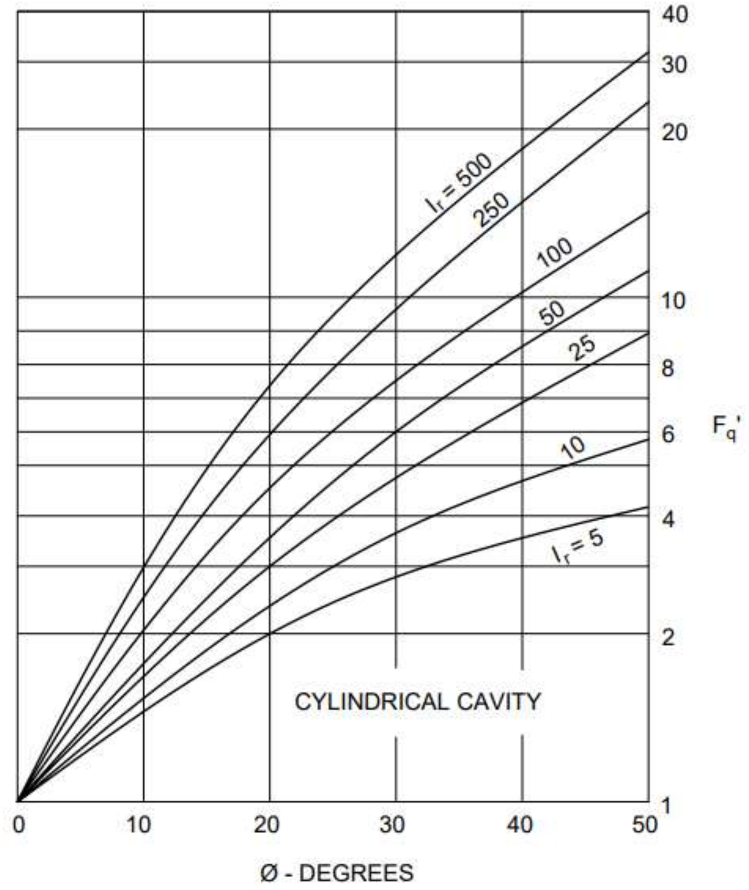


FIG. 8 VESIC CYLINDRICAL CAVITY

I_r is the rigidity index and can be calculated using the following formula:

$$I_r = \frac{E}{2(1+\mu)(c + q\tan\emptyset_c)}$$

where

E = Modulus of elasticity of the surrounding soil in which cavity expansion is occurring;
μ = Poisson’s ratio of the surrounding soil;
c = cohesion of the surrounding soil;
q = mean stress within the zone of failure; and
$\emptyset_c$ = friction angle of the material of the stone column.

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, A = 0.866 S^2

Effective area of stone column including the intervening soil for square pattern, A_s = 1.0 S^2

where, S = spacing of the stone columns.

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

$$A_g = A - A_s = A - \frac{\pi D^2}{4}$$

Safe load taken by the intervening soil, $Q_3 = q_{safe} A_g$ ....(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 $\emptyset$, the capacity may be estimated by using Bell's formula for passive pressure:

$$\sigma_{\mathrm{rL}} = P_{\mathrm{p}} = \gamma z k_{\mathrm{p}} + 2C_u\sqrt{k_{\mathrm{p}}} \qquad \text{....(6)}$$

where

P_{p} = passive pressure;
z = average bulge depth which is equal to 2 times the column diameter;
γ = effective unit weight of soil within the influence zone;
C_{u} = cohesion of the soil surrounding the column; and
k_{p} = passive pressure coefficient of soil = $\frac{(1+\sin\emptyset_{\mathrm{g}})}{(1-\sin\emptyset_{\mathrm{g}})}$, where, $\emptyset_{\mathrm{g}}$ is the 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:

$$\sigma_{\mathrm{v}} = \sigma_{\mathrm{rL}} K_{\mathrm{pcol}} = \frac{(1+\sin\emptyset_{\mathrm{c}})}{(1-\sin\emptyset_{\mathrm{c}})}$$

Safe load on column, $Q_1 = \sigma_{\mathrm{v}}\left(\frac{\pi/4\, D^2}{2}\right)$ ...(7)

A-2.2 The surcharge effect (Q_2) and bearing support of the intervening soil (Q_3) may be obtained as per **A-1.2** and **A-1.3**, respectively. However, the ultimate bearing pressure of mixed soil, q_{ult} shall be obtained as per IS 6403.

q_{safe}, the safe bearing pressure of soil will be given by (q_{ult}/2.5), where 2.5 is the factor of safety.

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 on the pattern of columns, as follows:

Sl No.	*Pattern*	*Area for Column*
(1)	(2)	(3)
i)	Triangular	0.866 S^2
ii)	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-3.4 The load capacity of the stone columns computed as in accordance with **A-1.3** should be verified by load test as per **13**.

A-4 ESTIMATION OF ULTIMATE LOAD CARRYING CAPACITY OF A STONE COLUMN USING PRIEBE METHOD

A-4.1 The Priebe's stone column design method refers to the improving effect of stone columns in a soil which is otherwise unaltered in comparison to the initial state. The improvement factors are computed as follows.

$$n_1 = 1 + \frac{\overline{A_\mathrm{s}}}{A} \cdot \left[\frac{1/2 + f\left(\mu_s, \overline{A_\mathrm{s}/A}\right)}{k_{\mathrm{aCol}} \cdot f\left(\mu_s, \overline{A_\mathrm{s}/A}\right)} - 1\right] \quad \text{. . . (8)}$$

where

$$\frac{\overline{A_\mathrm{s}}}{A} = \frac{1}{\frac{A}{A_\mathrm{s}} + \Delta(\frac{A}{A_\mathrm{s}})} \quad \text{. . . (9)}$$

$$\Delta\left(\frac{A}{A_\mathrm{s}}\right) = \frac{1}{\left(\frac{A_\mathrm{s}}{A}\right)'} - 1 \quad \text{. . . (9a)}$$

$$\left(\frac{A_\mathrm{s}}{A}\right)' = -\frac{4.K_{\mathrm{a.col}}.\left(\frac{D_{\mathrm{col}}}{D_{\mathrm{soil}}} - 2\right) + 5}{2.\left(4.K_{\mathrm{a.col}} - 1\right)} \pm \frac{1}{2}\sqrt{\left[\frac{4.K_{\mathrm{acol}}.\left(\frac{D_{\mathrm{col}}}{D_{\mathrm{soil}}} - 2\right) + 5}{4.K_{\mathrm{acol}} - 1}\right]^2 + \frac{16.K_{\mathrm{acol}}.\left(\frac{D_{\mathrm{col}}}{D_{\mathrm{soil}}} - 1\right)}{4.K_{\mathrm{acol}} - 1}} \quad \text{. . . (9b)}$$

$$f\left(\mu_{s,}\ \frac{\overline{A_\mathrm{s}}}{A}\right) = \frac{(1 - \ \mu_s).(1 - \frac{\overline{A_\mathrm{s}}}{A})}{1 - 2\mu_s + \frac{\overline{A_\mathrm{s}}}{A}} \quad \text{. . . (10)}$$

$$K_{\mathrm{aCol}} = \ tan^2\ (45° - \frac{\emptyset_\mathrm{s}}{2}) \quad \text{. . . (11)}$$

Applying (9), (10) and (11) in (8), n_1 is calculated. Further, applying depth factor f_{d}, n_2 is estimated as shown below.

$$n_2 = n_1 \times f_{\mathrm{d}} \qquad \text{. . . (12)}$$

where

$$f_{\mathrm{d}} = \frac{K_{\mathrm{o.col}}.\, p_{\mathrm{col}} - p_{\mathrm{soil}}}{K_{\mathrm{o.col}}.\, p_{\mathrm{col}} + K_{\mathrm{o.col}}.\, \sum(\gamma_{\mathrm{col}}.\, \Delta t) - p_{\mathrm{soil}} - \sum(\gamma_{\mathrm{soil}}.\, \Delta t)}$$

. . . (13)

$$K_{\mathrm{o.Col}} = 1 - \ sin\emptyset_{\mathrm{s}}$$

. . . (13a)

$$\frac{p_{\mathrm{col}}}{p_{\mathrm{soil}}} = \frac{1/2 + f\left(\mu_S, \overline{A_{\mathrm{s}}/A}\right)}{k_{aCol} \cdot f\left(\mu_S, \overline{A_{\mathrm{s}}/A}\right)}$$

. . . (13b)

$$P_{\mathrm{col}} = \frac{p}{\frac{\overline{A_{\mathrm{s}}}}{A} + \frac{1 - \overline{A_{\mathrm{s}}/A}}{p_{\mathrm{col}}/p_{\mathrm{soil}}}}$$

. . . (13c)

Here control for the maximum improvement factor is applied which guarantees that settlement of the columns resulting from its inherent compressibility does not exceed the settlement of the surrounding soil resulting from its compressibility by the loads which are assigned to each. Generally, the n_{max} shall be limited to 3.0.

$$n_{\mathrm{max}} = 1 + \frac{A_{\mathrm{s}}}{A} \cdot \left[\frac{D_{\mathrm{col}}}{D_{\mathrm{soil}}} - 1\right]$$

. . . (14)

As the shear properties of the installed material are better than those of the original soil the layer wise improved shear ($\emptyset$' and c') and stiffness ($D_{\mathrm{s}}{}'$) properties of the soil shall be estimated as below,

$$tan\emptyset' = m.\, tan\emptyset_{\mathrm{s}} + (1 - m) tan\emptyset_{\mathrm{g}}$$

. . . (15)

$$c' = (1 - m).\, c_{\mathrm{u}}$$

. . . (16)

where, the load share factor of column, m is given by,

$$m = \frac{n_1 - 1 + \frac{\overline{A_S}}{A}}{n_1} \qquad \text{. . . (17)}$$

$$D_s{}' = n_2 . D_{\mathrm{soil}} \qquad \text{. . . (18)}$$

For the purpose of the equations given above, the various symbols used in them shall mean the following:

n_1	=	Improvement factor with correction due to compressibility of the column material
n_2	=	Improvement factor with consideration of the effect of overburden pressure (depth factor)
n_{max}	=	Maximum improvement factor
A_{s}	=	Cross-sectional area of the column, m^2
A	=	Grid area/Area of the unit cell, m^2
μ_{s}	=	Poisson ratio of column
K_{aCol}	=	Coefficient of active earth pressure of the column
D_{col}	=	Constrained modulus of the stone column, kN/m^2
D_{soil}	=	Constrained modulus of soil, kN/m^2
$\emptyset_{\mathrm{s}}$	=	Friction angle of column material
$\emptyset_{\mathrm{g}}$	=	Friction angle of soil
f_{d}	=	Depth factor
p_{col}	=	Vertical stress in the column, kN/m^2
p_{soil}	=	Vertical stress in the soil, kN/m^2
Δt	=	Thickness of soil layer, m
K_{oCol}	=	Coefficient of earth pressure at rest condition of the stone column
p	=	Area load (foundation pressure or vertical stress), kN/m^2
$\emptyset'$	=	Improved friction angle, degrees
c’	=	Improved cohesion, kN/m^2
m	=	Load proportion of the column
$D_{\mathrm{s}}{}'$	=	Improved constrained modulus of soil, kN/m^2

In the above equations, the improvement factor n_1 is used for ultimate limit state conditions (that is, ULS for SBC) and n_2 is used for serviceability limit state conditions (that is, SLS for settlements). These improved stiffness and shear parameters shall be used in classical bearing capacity and settlement equations to estimate the improved SBC and settlements expansions;

A-5 A sample calculation for estimating improved parameters is presented below for guidance.

Foundation pressure	=	130 kN/m^2
Column spacing	=	1.52 m (triangular pattern)
Stone column diameter	=	0.75 m
Unit cell area	=	2.00 m^2
Load application level	=	EL +1.0 m
Column toe level	=	EL -10.0 m
Calculation depth	=	EL -20.0 m
Column material:		
Unit weight	=	19 kN/m^3, below EL -1.6m – 12 kN/m^3
Constrained modulus, D_{col}	=	1,00,000 kN/m^2
Friction angle, $\emptyset_s$	=	40º

Subsoil stratum:

Layer No.	Top level EL	Diameter of column	D_{soil}	γ	γ'	ϕ	c,	μ_s
	m	m	kN/m^2	kN/m³	kN/m³	degrees (º)	kN/m²	
1	1.0	-	50 000	19	9	35	0	0.33
2	0.0	0.75	20 000	18	8	25	5	0.33
3	-0.4	0.75	2 000	16	6	0	25	0.33
4	-1.0	0.75	1 000	15	5	0	20	0.33
5	-1.6	0.75	1 000	15	5	0	20	0.33
6	-8.2	0.60	10 000	17	7	0	30	0.33
7	-9.0	0.60	20 000	19	9	30	0	0.33
8	-10.0	-	20 000	19	9	30	0	0.33
9	-20.0	-	20 000	19	9	30	0	0.33

Step by step procedure for calculating improved parameters of Layer No. 5 at EL - 1.6 m to EL - 8.2 m is given below:

Calculation of improvement factor n_1:

$D_{\mathrm{col}}/D_{\mathrm{soil}}$	=	100 000/1 000
	=	100
K_{oCol}	=	$tan^2\ (45° - \frac{40^{\circ}}{2})$
	=	0.217

$\left(\frac{A_s}{A}\right)'$	=	$-\frac{4\times 0.217.(100-2)+5}{2\times(4\times 0.217-1)}-\frac{1}{2}\sqrt{\left[\frac{4\times 0.217\times(100-2)+5}{4\times 0.217-1}\right]^2+\frac{16\times 0.217\times(100-1)}{4\times 0.217-1}}$
	=	0.956
$\Delta\left(\frac{A}{A_s}\right)$	=	(1/0.956)-1
	=	0.046
$\frac{\overline{A_s}}{A}$	=	$\frac{1}{\frac{2}{0.44}+0.046}$
	=	0.218
$f\left(\mu_{s,}\ \frac{\overline{A_s}}{A}\right)$	=	$\frac{(1-\ 0.33).(1-0.218)}{1-(2\times 0.33)+0.218}$
	=	0.938
n_1	=	$1+0.218\ \left[\frac{0.5+0.938}{0.217\ \times 0.938}-1\right]$
	=	2.32

Calculation of improvement factor, f_d:

Overburden pressure of soil at Centre of i^{th} layer (kN/m²)	=	(1x19)+(0.4x18)+(0.6x16)+(0.6x15)+(0.5x6.6x5)
	=	61.3
Overburden pressure of column at Centre of i^{th} layer (kN/m²)	=	(1x19)+(0.4x19)+(0.6x19)+(0.6x19)+(0.5x6.6x12)
	=	89.0
K_{oCol}	=	1 – sin(40°)
	=	0.357
$\frac{P_{\text{col}}}{P_{\text{soil}}}$	=	$\frac{0.5+0.937}{0.218\ \times\ 0.937}$
	=	7.04
Stress in the column, P_{col} (kN/m²)	=	$\frac{130}{0.218+\frac{1-0.218}{7.04}}$
	=	394.69
Stress in the soil, P_{soil} (kN/m²)	=	$\frac{394.69}{7.04}$
	=	55.98
Δt (m)	=	(8.2 – 1.6)
	=	6.6
f_{d}	=	$\frac{(0.357\times 394.69)-55.98}{(0.357\times 394.69)+(0.357\times 89)-55.98-61.3}$
	=	1.53

Calculation of n_{max} and n_2

n_2	=	1.53 x 2.32
	=	3.55 > 3.0, Limit to 3.0.

Calculation of final improved composite parameters

Load share factor of column, m	=	$\frac{2.32 - 1 + 0.219}{2.32}$
	=	0.66
Improved friction angle, $\emptyset'$	=	$\tan^{-1}(0.66 \times \tan(40^o) \times (1 - 0.66)\tan(0))$
	=	29^o
Improved cohesion, c’	=	(1– 0.66) x 20
	=	6.8 kN/m²
Improved stiffness, $D_s{}'$	=	3.0 x 1000
	=	3 000 kN/m²

ANNEX B
(*Clause* 9.3)

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 (Part 1). Settlements of the treated ground may be estimated using the reduced stress method based on the stress concentration ratio, *n* and the area 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:

$$n = \sigma_s/\sigma_g$$

where

σ_s = vertical stress in compacted columns under the applied stress, σ; and
σ_g = vertical stress in surrounding ground under the applied stress, σ.

$$\left(A_s + A_g\right)\sigma = A_s\sigma_s + A_g\sigma_g$$

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

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

$$\sigma_s = \frac{n\sigma}{1+(n-1)a_s} = \mu_s\ \sigma$$

d) 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 — Above equation is based on the assumption that the settlement of the strata underlying the column tip is added to the settlement of the reinforced ground.

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

$$S = m_{\mathrm{v}} \sigma H$$

f) Settlement reduction ratio, β is defined as:

$$\beta = \frac{Settlement\ of\ treated\ soil}{Settlement\ of\ untreated\ soil} = \frac{S_{\mathrm{t}}}{S} = \frac{1}{1 + (n-1)a_{\mathrm{s}}}$$

B-2 ESTIMATION OF CONSOLIDATION RATE OF STONE COLUMN REINFORCED GROUND

In a cohesive soil reinforced with stone columns, water moves toward the stone column in a curved path having both vertical and radial components of flow as illustrated in Fig. 9.

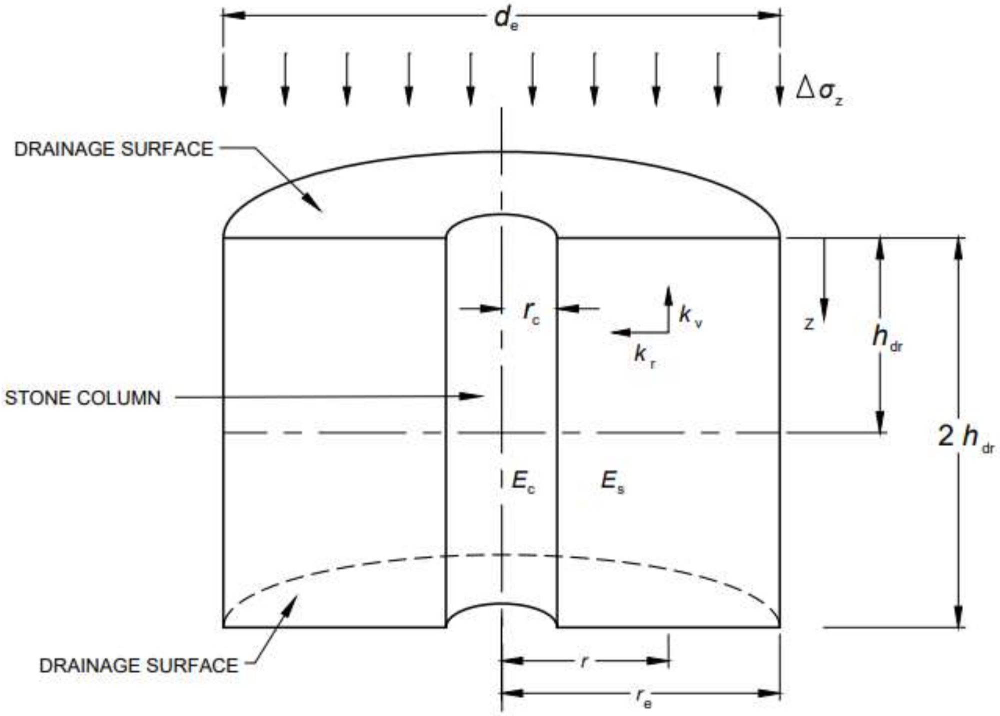


FIG. 9 FLOW OF WATER WITHIN UNIT CELL TO STONE COLUMN DRAIN - SECTION VIEW

As per theory of consolidation, the total degree of consolidation (U_{rv}) can be expressed as

$$U_{\mathrm{rv}} = 1 - (1 - U_{\mathrm{v}})(1 - U_{\mathrm{r}})$$

where

U_{v} = degree of consolidation for vertical flow; and
U_{r} = degree of consolidation for radial flow.

U_{v} and U_{r} are the function of time factors in vertical (T_{v}) and radial directions (T_{r}).

Simplified formula for estimation of total degree of consolidation can be expressed as below,

$$U_{\mathrm{rv}} = 1 - \frac{8}{\pi^2} exp^{-[8/F(N)]T_{\mathrm{r}}' - [\pi^2/_4]T_{\mathrm{v}}'}$$

where

$T_{\mathrm{r}}' = c_{\mathrm{r}}'\, t/{d_{\mathrm{e}}}^2$,= time factor in the radial flow; and
$T_{\mathrm{v}}' = c_{\mathrm{v}}'\, t/H^2$ = time factor in the vertical flow.

where

H = thickness of soil from a free-draining horizontal surface to an impervious one;
F(N) = $\left[\left\{\frac{N^2}{(N^2-1)\ln(N)}\right\} - \left\{\frac{(3N^2-1)}{(4N^2)}\right\}\right]$ where, $N = \frac{d_{\mathrm{e}}}{d_{\mathrm{c}}}$; and

c_{v}' and c_{r}' = modified coefficients of consolidation given by the equations below:

$$c_{\mathrm{v}}' = c_{\mathrm{v}}\left(1 + n_{\mathrm{s}}\frac{1}{N^2-1}\right); \text{ and}$$

$$c_{\mathrm{r}}' = c_{\mathrm{r}}\left(1 + n_{\mathrm{s}}\frac{1}{N^2-1}\right).$$

Many field studies have shown that steady-stress concentration ratios (n) for stone column reinforced foundations are in the range of 2 to 6.

B-3 A solved example for estimation of consolidation rate of stone column reinforced ground is presented below for guidance.

Stone Columns Properties		**Remarks**
Diameter (d)	0.8 m	Typical values assumed for sample calculation
Spacing (S)	2.0 m	
Grid type	Triangular	

Stone columns constrained modulus	120 000 kPa	
Soil Properties		**Remarks**
Soil constrained modulus	5 000 kPa	Typical values assumed for sample calculation
Coefficient of consolidation in vertical direction (c_v)	0.5 m^2/yr	
Coefficient of consolidation in radial direction (c_r)	1.0 m^2/yr	
Thickness of Layer (H)	10 m	In case of two-way drainage, drainage path is 5 m
Total degree of consolidation, U_{rv}		**Remarks**
Time	5 months	Typical values assumed for sample calculation
Contamination of stone columns (C_{sc})	15 percent	
dc (with contamination)	0.68 m	(1 - C_{sc}/100) X d
de	2.1 m	de = 1.05 X S (triangular pattern); and 1.13 X S (square pattern)
N (d_e/d_c)	3.088	
F(N)	0.536	Steady-stress concentration ratios (ns) for stone column reinforced foundations are in the range of 2 to 6.
n_s	3	
C_v'	0.7 m^2/yr	
C_r'	1.4 m^2/yr	
T_v'	0.003	
T_r'	0.128	
U_{rv}	88 percent	

ANNEX C

(*Clause* 9.4)

LIQUEFACTION POTENTIAL OF IMPROVED GROUND TREATED WITH STONE COLUMNS

C-1 Ground improvement using stone columns in seismic areas mitigates the liquefaction potential of the soil. The stone columns installed in liquefiable soil has the following effects:

a) Increase cyclic resistance ratio (CRR) by densifying the soil (exclusively for sands, densification effect);
b) Reduce cyclic stress ratio (CSR) by stiffer columns by reinforcement effect; and
c) Limit the rise in excess pore water pressure (drainage effect).

C-2 Installation of stone columns using vibroflot densifies the sands. The densification effect due to installation of stone columns is preferred to be accounted in post improvement liquefaction assessment. As a preliminary guide, the following equation is recommended to estimate the increase in SPT N value and cone resistance q_c value for sands:

$$N_{1(60)\text{cs,improved}} = \frac{N_{1(60)\text{cs,unimproved}}}{\left[0.776(1.121\times10^{-9})^{A_\text{r}}\right] + \left[\{0.025 - 0.0194\{(1.121\times10^{-9})^{A_r}\}\}.N_{1(60)\text{cs,unimproved}}\right]}$$

$N_{1(60)\text{cs,improved}}$ is the predicted clean sand SPT N value corrected for overburden and 60 percent energy efficiency after installation of stone columns using vibroflot. $N_{1(60)\text{cs,unimproved}}$ is the clean sand SPT N value corrected for overburden and 60 percent energy efficiency before installation of stone columns. A_r is the replacement ratio evaluated as area of stone column divided by the tributary area. In case A_r greater than 20 percent is provided, A_r = 20 percent shall be used in above equation for conservative estimate. The above equation may be used only when fines content is less than 15 percent.

Similarly, the cone resistance ($q_\text{c,improved}$) after installation of stone columns using vibroflot is estimated as,

$$q_\text{c,improved} = \frac{q_\text{c,unimproved}}{A_\text{r}(0.0097q_\text{c} - 2.33) + 0.0028q_\text{c} + 0.33216}$$

$q_\text{c,unimproved}$ is the cone resistance before installation of stone columns and in case A_r greater than 12 percent is provided, A_r should be considered as 12 percent for conservative estimate. The above equation may be considered only when friction ratio is less than 1 percent.

The predicted improved penetration resistance as estimated above shall be verified against the field tests conducted after installation of stone columns using vibroflot.

C-3 The factor of safety against liquefaction is evaluated using Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR) according to IS 1893 (Part 1). For evaluation of factor of safety against liquefaction after installation of stone columns, CSR is reduced by a factor (α) to account for the reinforcement effect of stone columns, which is given by the following equation:

$$\alpha = \frac{p_{\mathrm{soil}}}{p} = \frac{1}{(A/A_{\mathrm{s}})} = \frac{K_{\mathrm{aCol}}(1 - A_{\mathrm{s}}/A)}{[(A_{\mathrm{s}}/A) + K_{\mathrm{aCol}}(1 - A_{\mathrm{s}}/A)^2]}$$

where

$$K_{\mathrm{aCol}} = tan^2\left(45° - \frac{\emptyset_s}{2}\right)$$

where

$\emptyset_{\mathrm{s}}$ = friction angle of stone column.

The reduced CSR, that is, $\mathrm{CSR_{red}}$ is computed as α (CSR).

The procedure highlighted above is simplified procedure for evaluating the efficacy of stone column improved ground against liquefaction.

ANNEX D

(*Clause* 10)

INSTALLATION TECHNIQUES OF STONE COLUMNS

D-1 NON-DISPLACEMENT METHOD/REPLACEMENT METHOD

The following replacement methods shall be used for installation of stone columns:

a) Bailer and casing method;
b) Rotary drill method; and
c) Deep vibro-techniques using wet top feed method.

D-1.1 Bailer and Casing Method

D-1.1.1 Installation using the bailer and casing method shall be done as per the procedure given below:

a) The borehole should be advanced by using a bailer while its sides are retained by a casing.
b) The water level in the casing should be maintained at around 2.0 m above the surrounding ground water level to minimize disturbance at the bottom of the hole and to avoid loss of ground due to suction.
c) Care should be taken during drilling that casing is always ahead of boring to avoid excess diameter of borehole.
d) The bailer diameter should be 75 mm to 100 mm less than the internal diameter of the casing, to avoid suction effects.
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 should be 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 stone of 75 mm down to 2 mm should be placed in the casing to fill it to about 1 m to 1.5 m depth.
j) After placement of this charge, the casing should be withdrawn making sure that its bottom invariably remains a minimum of 0.5 m into the stones.
k) The loose charge below the bottom of the casing should be 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 should 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 **D-1.1 (k).**

n) It may be considered 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 **D-1.1 (m)**, the next charge is placed in the casing and it is rammed in accordance with the **D-1.1 (k)** to **D-1.1 (m)**. The procedure shall be repeated till a stone column of the desired length has been formed and the casing completely removed.

D-1.1.1 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 **D-1.1(d)**.

D-1.2 Rotary Drill Method

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

D-1.3 Deep Vibro-techniques Using Wet Top Feed Method

D-1.3.1 The equipment for constructing stone column by deep vibro-techniques using wet top feed method should meet the following requirements:

a) Vibroflot, a poker vibrator is available in various diameters, length and weight. Selection of the equipment shall be done after giving due consideration to the soil type, its strength characteristics, depth of treatment, etc. A typical vibroflot probe is shown in Fig. 10 and Fig. 11. It consists of two parts:

    1) Vibrator, and
    2) Follow-on pipes/tubes.

b) 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 should be horizontal with the body cycling around a vertical axis.

c) While the vibrator is in motion, the follow up pipe should remain almost stationary. This is achieved by inserting a universal connection (vibration isolator) between the two parts. The follow-on tube which has diameter slightly 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 should have a power pack as a separate unit placed adjacent to the suspending crane.

d) Other auxiliary equipment required 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.

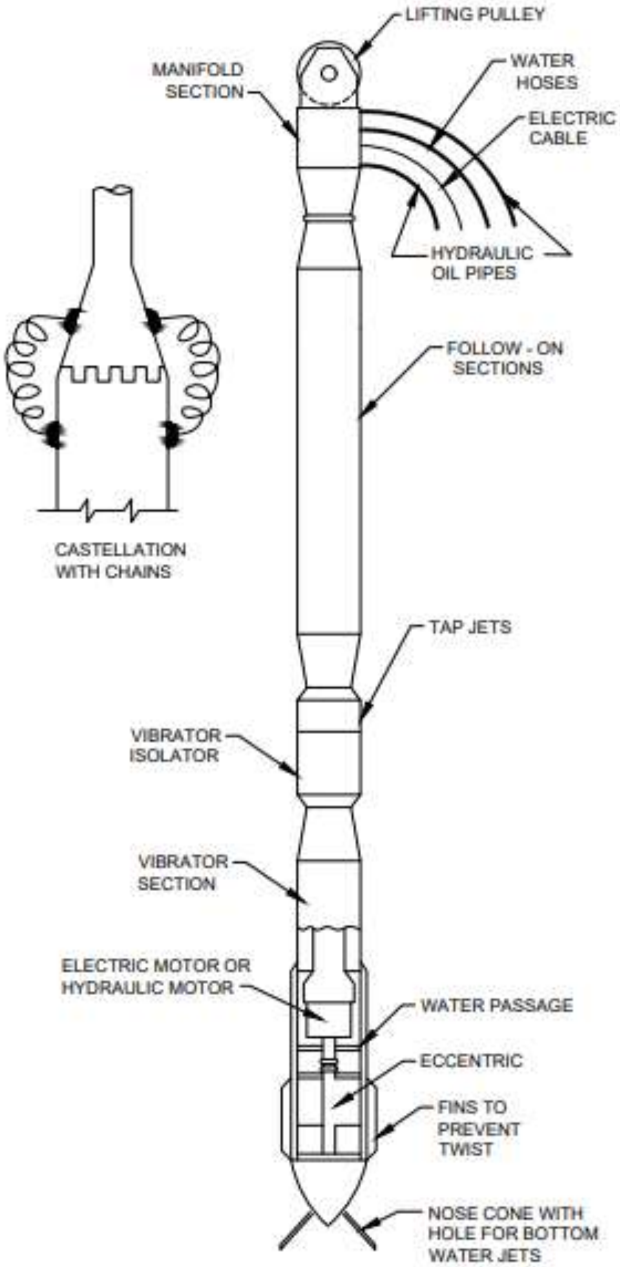


FIG. 10 STONE COLUMN INSTALLATION USING WET TOP FEED METHOD

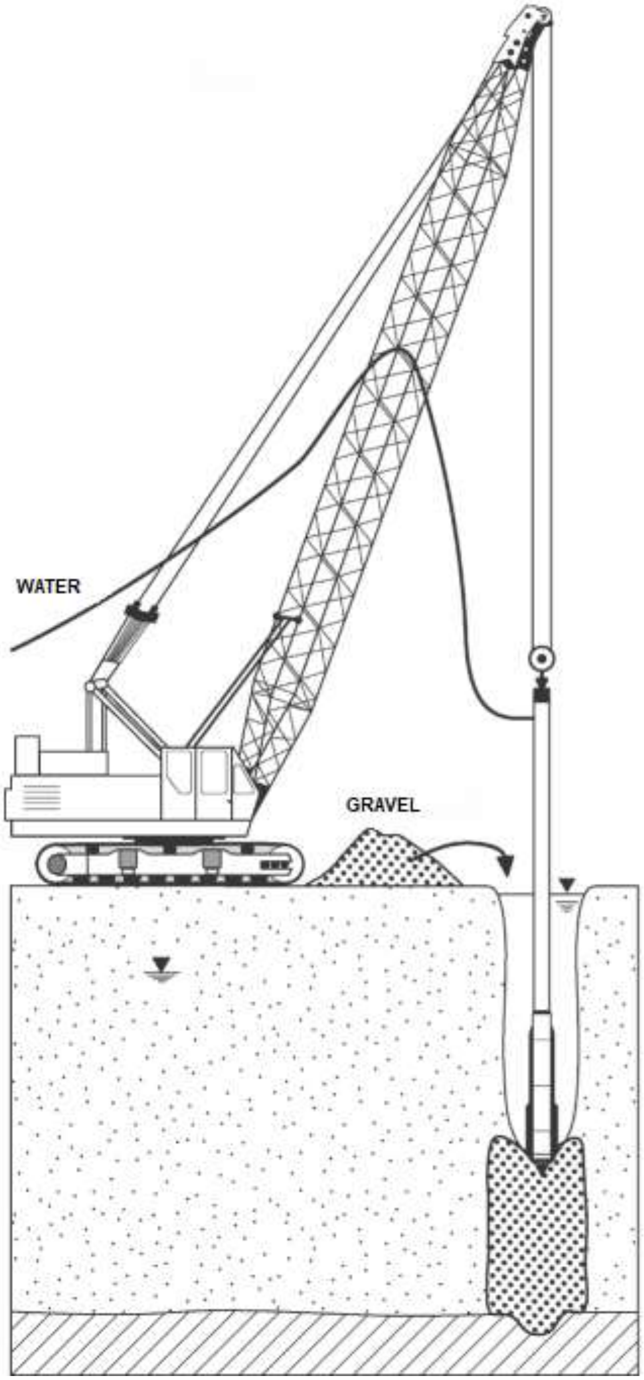


FIG. 11 STONE COLUMN INSTALLATION USING WET TOP FEED METHOD

D-1.3.2 ***Compaction Procedure***

The following procedure should be followed for constructing the stone column:

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 soil directly under the vibroflot nose forming a hole. This operation allows 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 should be reduced suitably. An 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 soils from the hole. When the water flow continuously returns to the surface, the probe should be raised by suitable lift, say 1.5 m and the backfill should be 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.
c) Care shall be taken during construction for not allowing the side walls of the hole to collapse. This is avoided by keeping the water flowing throughout construction to help stabilize the side walls of the hole.
d) Stone should be 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. 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 required compaction/desired diameter 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 should then be lodged in and the compaction cycle should be 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.
h) The personnel operating the machine should be experienced enough to be able to quickly identify the situations, such as premature quitting of shoving backfill 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.

D-2 DISPLACEMENT METHOD

D-2.1 The following displacement method shall be used for installation of stone columns:

a) Deep vibro techniques using dry bottom feed method; and
b) Rammed stone columns.

D-2.1 Deep Vibro Techniques Using Dry Bottom Feed Method

D-2.1.1 The following procedure should be adopted for installing stone columns using deep vibro techniques using dry bottom feed method:

a) In dry bottom feed method, penetration to the desired depth shall be assisted by the action of vibrations, with or without pull-down facility.
b) As the vibrator remains in the hole during column construction, the process can operate successfully in unstable hole conditions.
c) The bottom-feed depth vibrator has a heavy duty supply tube located at one side of the tube and permanently fixed to the vibrator forming a fully integrated vibrator/granular material supply.
d) The supply tube bends inwards at the vibrator tip to ensure a central location for the supply of granular material. The general arrangement is shown in Fig. 12.
e) The cycle of operations for this completely dry process shall be as follows:

    1) The vibrator is positioned on the ground at the treatment point location; and the whole system is charged with granular material.
    2) With the granular material in the supply tube acting as a plug at the tip of the vibrator, assisted as necessary by compressed air and under the combined action of the vibrations and its weight, using an additional pull down force, if necessary, the vibrator penetrates the ground to the required depth.
    3) The stone column is then formed and compacted by lifting the vibrator, holding the lift for a short time to allow the granular material to run, and then forcing the vibrator down on the charge of granular material to compact and tightly interlock it with the surrounding soil.
    4) This is repeated, charging the system with granular material as necessary, until a compact stone column is formed up to required level.

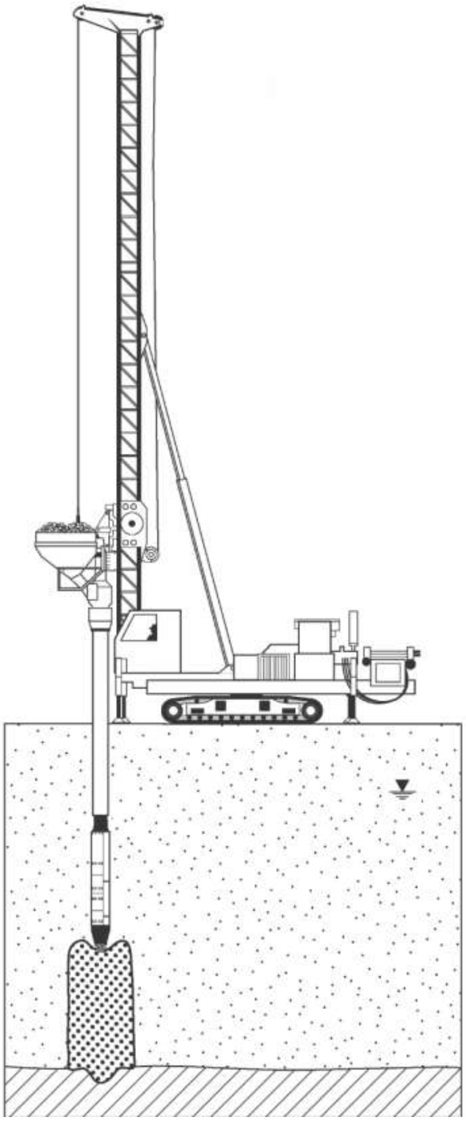


FIG. 12 STONE COLUMN INSTALLATION USING DRY BOTTOM FEED METHOD

D-2.2 Rammed Stone Columns

D-2.2.1 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 densify the column.

D-2.2.2 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.

ANNEX E

(*Clause* 15.2)

TYPICAL DATA SHEET FOR RECORDING INSTALLATION OF STONE COLUMNS

NAME OF AGENCY:

STONE COLUMN INSTALLATION RECORD

Name of Work:
Drawing No.:

Name of Client:
Date/Shift:

Stone column number		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:		Total time taken for compaction of all batches of stones:	
Method of installation		Total time taken for installation of stone column:	
Type of equipment used for installation of column along with the details of their size and capacity		Length of stone column from GL:	
Compaction efforts during penetration and compaction process		Total volume of stones consumed:	
Any other observation			