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A Practical Approach For Computing Soil Bearing Capacity Under Shallow Foundations Using Vibro-Replacement Method

Mansour N. Jadid
(Department of Building Science & Technology, University of Dammam, Saudi Arabia)

ABSTRACT : *This paper presents a practical approach for designing, erecting, and testing stone columns using the vibro-replacement method to improve soil bearing capacity under shallow foundations (isolated and raft foundations) for any typical building under small or medium loading conditions. Usually, the vibro-replacement method is used in soils with cohesive layers of mixed deposits, loose sand, or both. Vibro-replacement methods create reinforced, compacted columns in poor soils, which provide reinforcement for soft cohesive soils to improve bearing capacity and reduce settlement. Vibro technologies provide quick and cost-effective solutions for areas of weak and unconsolidated soils. Usually, a geotechnical consultant suggests alternative methods for improving the engineering characteristics of subsoil at a selected site by several methods such as piles, complete replacement using backfill, and improving the subsoil using the vibro-replacement method (stone columns), the method considered in this study. A backfill size of aggregate material from limestone quarries ranging from 2.50 mm to 10 mm is recommended for stone columns. A 300 mm-thick layer of well-compacted fill material is suggested as a sandwich between the bottom of the foundation and the stone columns as a practical procedure after completion of soil improvement and removal of mud to provide uniformity of foundation loading on the soil.*

Keywords **-** *Backfill, bearing, borehole, foundation, practical, shallow, stone columns, penetration, Soil*

I. INTRODUCTION

Constructing buildings on weak soil normally requires soil investigations to improve the soil bearing capacity and reduce settlement. Initially, borehole testing and geotechnical investigations are carried out to a certain depth below the surface to determine the existing soil conditions. This makes it possible to determine the appropriate method for improving the soil bearing capacity and reducing settlement by selecting the method that satisfies the loading conditions and is cost-effective.

The improvement of weak soil deposits by stone columns has now become a well-established method for improving the bearing capacity and settlement characteristics of soft soils, [1,2]. A method to improve collapsible soil by using encapsulated stone columns, which is efficient for lightweight structure building has been established [3]. The behavior of a stone column in a collapsible fill and a column in a non-collapsible fill where reported by suggesting solution for the problem of stone column failure [4].

Stone columns are constructed in cases where soil improvement can be achieved by reinforcing weak soils with densely compacted granular columns. This method provides for reinforcement of soft cohesive soils to improve bearing capacity, reduce settlement, and improve the stability of embankments and slopes. The stone column technique is ideally suited for improving soft silts, clays, and loose silty sands.

When properly installed within soft soil, the stone column treatment produces a composite material with unique characteristics. The high internal frictional resistance of the stone conveys a significant frictional component to the treated composite, improving both its strength and its deformational behavior. The level of improvement depends on the soil type, column installation technique, relative spacing of the columns, and column diameter. The unique characteristics of stone columns can provide innovative and cost-effective solutions for many unusual geotechnical problems as well as for many more routine applications. Gravel backfill is deposited into holes in increments of 0.4 to 0.8 m and compacted by the probe, which simultaneously displaces the material radially into the soft soil. The diameter of the resulting stone column is usually between 0.6 and 1.0 m, but columns of larger diameter can be constructed using two or three vibrators simultaneously as mentioned [2].

Generally, a proper installation is essential for producing high-quality stone columns. Because stone is a frictional material possessing negligible cohesion, the confining pressure applied by the soil is of vital importance. As quality assurance to ensure proper vibro-replacement execution, the following procedure is recommended:

- A pre-test of minimum one Dutch cone penetration test as suggested [5] or one borehole for every 500 square meters

- A post-test of at least one Dutch cone test, [5] or one borehole for every 500 square meters
- A full-load plate test to verify the bearing capacity and settlement after the soil has been improved.

II. MECHANISM FOR SOIL IMPROVEMENT AND SUBSOIL CONDITIONS

The mechanism of the vibro-replacement method for soil improvement under shallow foundations proceeds as follows:

- Design of the stone columns
- Procurement of backfill material
- Pre-treatment Dutch cone penetration test
- Stone column construction
- Post-treatment Dutch cone penetration test
- Plate load tests
- Final report submission.

Ground improvement by the stone column technique can be used for any selected building to improve the soil capacity under the foundations. The present investigation addresses shallow isolated and raft foundations constructed according to design, and a final geotechnical report is required for a general review of the soil condition. Assuming that the soil conditions are based on the borehole logs, the subsoil consists of silty sand up to about 1.5 meters in depth, followed by very loose silty sand known up to 3.5 meters in depth. This layer is underlain by medium dense to dense silty sand up to a variable depth between 5.5 to 6.5 meters below the existing grade. The silty layer is followed by gravel and silty sand. A specialized contractor must be hired for the installation of stone columns under foundation areas to improve the bearing capacity of the existing soil so that settlement as a result of foundation loads remains within acceptable limits as determined by the design consultant.

Values from the borehole for Standard Penetration Test –SPT– as specified [6] obtained from the geotechnical report were plotted against the depth of the borehole log, and a design standard penetration test (SPT) profile was selected for the purposes of soil improvement design and settlement analysis. Suitable soil parameters are designed for the subsoil layer depending on the soil classification.

Table 1 shows the stone columns as designed for the unimproved soil parameters used in this study. The design SPT values were converted to Cone Penetration Test (CPT) cone resistance based on the q_c/N ratio for sand. According to [7], the E-modulus used is $2q_c$, and the E-modulus proposed was between 2.5 and 3.5 q_c. The existing soil E-modulus was established using the correlation in this study by using Equation (1), and the values are listed in Table 1:

$$E = 2.5\, q_c \qquad (1)$$

Where is E = soil modulus and q_c is the cone resistance

III. DESCRIPTION OF FOUNDATIONS

The soil improvement depth depends on the existing soil density, soil type, foundation dimensions, and foundation loads. The depth of soil improvement is selected so that the foundation settlement is less than allowable limits. The bottom level of the foundation was selected as the working level. Table 2 shows footing dimensions for a typical building. Figure (1) shows the foundation plan for a typical building, and Figure (2) shows the stone column erection layout under the foundations, with a section showing the dimensions of the four stone columns.

IV. BEARING CAPACITY, ALLOWABLE SETTLEMENT AND IMPROVEMENT OF SOIL DESIGN

Assuming that the target allowable bearing capacity after soil improvement under the foundations of this building is 200 kN/m^2, the maximum allowable settlement specified for an isolated footing is 25 mm, and the maximum allowable settlement for a raft foundation is 50 mm.

The VIBRI software developed [8], which is based on the design criteria provided by 'PRIEBE', was used for soil design improvement. Based on the given bearing capacity for existing soil conditions, the VIBRI program calculates the suitable spacing of stone columns of a specified nominal diameter, depth, and quality to provide the required improvement. The improvement factor is denoted in the VIBRI output file as *n2*.

In the VIBRI output, the *n2* values are used to enhance the existing soil properties and the Young's modulus of elasticity and thus to determine the corresponding settlement after soil improvement. The proposed spacing is selected if the settlement is within the specified allowable limits. The settlement analysis is carried out using the SPANNI program, [8] that enables estimation of settlement after soil improvement. The existing soil parameters are used in the VIBRI program to design the stone column spacing for the given bearing pressure of 200 kPa. The improvement factors obtained from the VIBRI program were used to calculate the improved E-values of each subsoil layer.

Table 1 Parameters for stone columns in unimproved soil used in this investigation

Depth below EGL meter	Design SPT	Unit weight kN/m^3	Submerged unit Weight kN/m^3	Angle of internal friction	Cohesion S_u kPa	Relationship for E-value	Unimproved E-value kN/m^2	Type of soil
0.00	8	15.0	28.0	28	kPa	$q_c /N=0.4$, $E=2.5q_c$	8000	sand
1.00	8	15.0	8.0	28	kPa	$q_c /N=0.4$, $E=2.5q_c$	8000	Sand
1.5	8	15.0	8.0	28	kPa	$q_c /N=0.4$, $E=2.5q_c$	8000	Sand
2.50	12		9.0	32	kPa	$q_c /N=0.4$, $E=2.5q_c$	12000	Sand
4.50	35		9.0	38	kPa	$q_c /N=0.4$, $E=2.5q_c$	35000	Sand
6.00	35		9.0	38	kPa	$q_c /N=0.4$, $E=2.5q_c$	35000	Sand
7.00	23		10.0	33	kPa	$q_c /N=0.4$, $E=2.5q_c$	23000	Sand
9.00	35		10	38	kPa	$q_c /N=0.4$, $E=2.5q_c$	35000	Sand

Note: Water level = 2.5 m below existing grade level (EGL)
Required bearing capacity = 200 kPa at 1.5 m below ground level
Bottom elevation of foundation = existing grade

Table 2 Footing dimensions

Footing	Width, m	Length, m
F01	1.0	1.0
F02	1.5	1.5
F02’	1.8	2.5
F03	3.0	3.0
F04	3.5	3.5
F05	4.0	4.0
F06	4.5	4.5
F07	4.8	4.8
F08	7.0	8.0
F09	8.0	8.0
F10	5.0	9.6
F11	5.0	10.0
F12	7.5	12.0
F13	5.5	16.4
F14	4.8	7.0

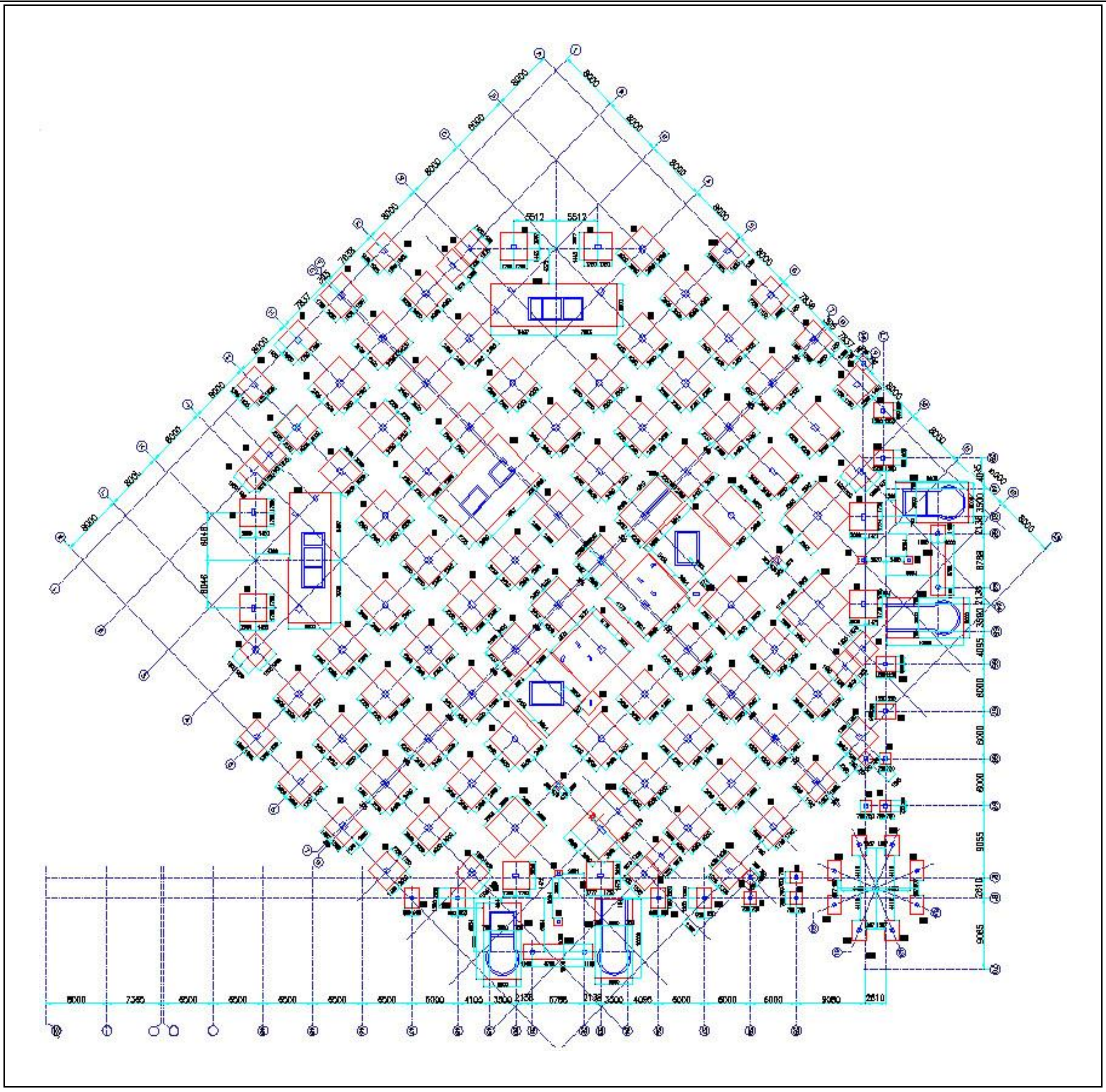

Figure 1 Typical foundation plan

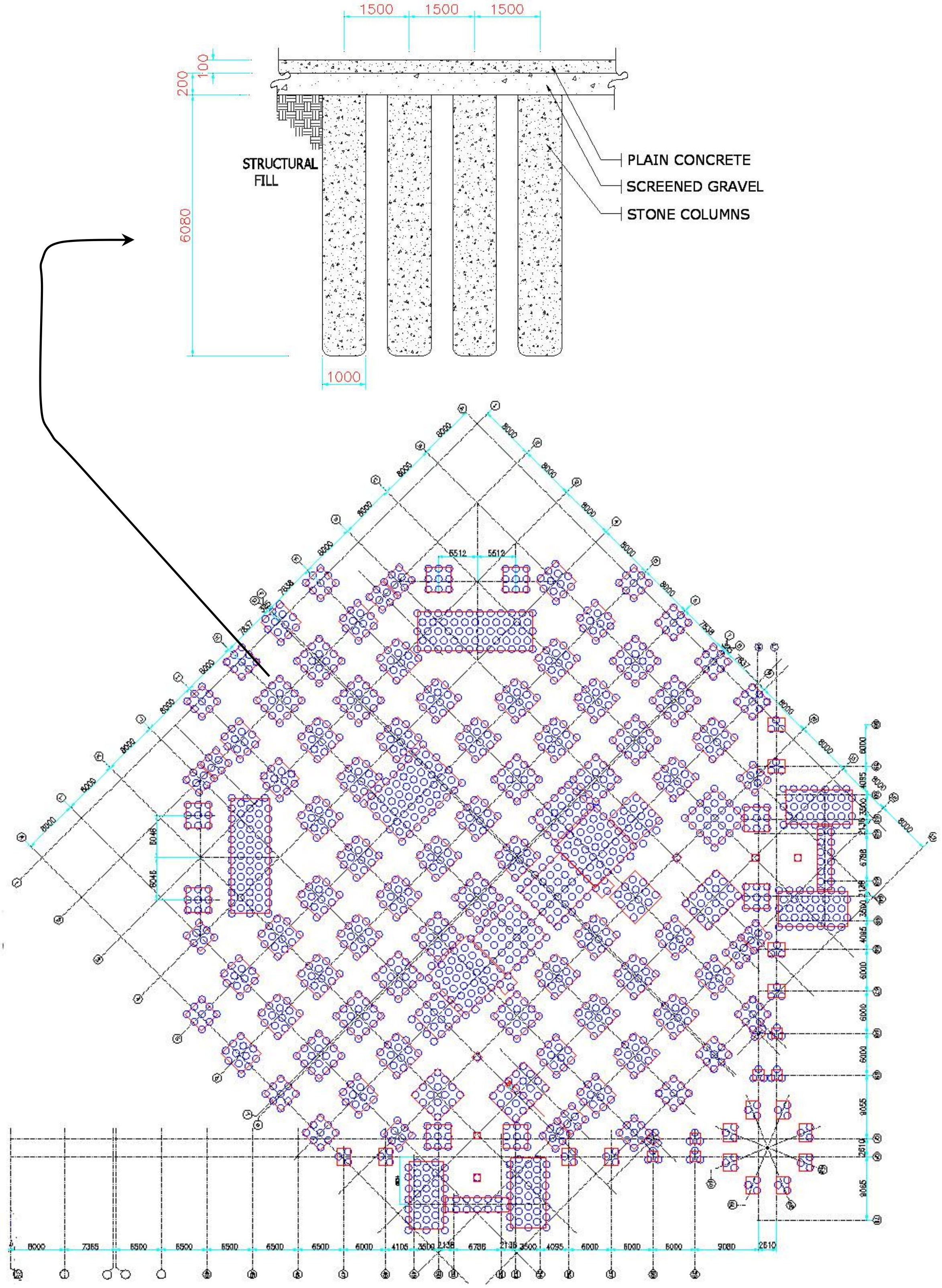

Figure 2 Layout for typical stone column erection

The VIBRI and SPANNI outputs can be summarized as follows:

Target bearing capacity = 200 kN/m^2

Nominal stone column diameter = 1000 mm

Stone column spacings on a 1.50 m by 1.50 m square grid and a 1.50 m by 1.50 m triangular grid are suggested for all the foundations as shown in Table 3.

Using the stone column proposal described above, the expected settlements after soil improvement are as follows:

- For isolated foundations of width less than or equal to 4.8 meters, the expected settlement is less than or equal to 25 mm

- For foundations of width between 4.8 meters and 8.0 meters, the expected settlement is less than or equal to 50 mm for a raft foundation.

Table 3 Area loading on square and triangular grids

Unit weight 20.0 kN/m^3	Below 2.5 m		Depth 12.0 kN/m^3
Below an area load on a square grid		Below an area load on a triangular column grid	
Column distance	1.5 m	Column distance	1.50 m
Row distance	1.5 m	Row distance	1.30 m
Grid area	2.25 m^2	Grid area	1.95 m^2
Load level	1.5 m	Load level	1.50 m

Note: Foundation pressure = 200.00 kN/m^2, Constrained modulus = 120.0 MN/m^2 ,Friction angle = 42.5 Degrees
Pressure coefficient = 0.19, Considered depth = 9.0 m

V. COMPUTATIONAL OF E-MODULUS

Table 4 shows the improvement factors obtained from the VIBRI program for square and triangular grids.

Table 4 Improvement factors Obtained from the VIBRI program for square and triangular grids

		Allowable bearing capacity = 200 KPa				
		1.5 m Square grid		1.5 m Triangular grid		
Depth from EGL (Top of layer) meter	Unimproved E-value kN/m^2	Improvement factor n_2 from VIBRI printouts	Improved E- value	Improvement factor n_2 from VIBRI printouts	Improved E-value	Remarks
0.00	8000	-		-		
1.00	8000	-		-		
1.50	8000	3.50	28000	4.02	32160	Stone Column
2.50	12000	3.51	42120	3.99	47880	Stone Column
4.50	35000	1.85	64750	1.98	69300	Stone Column
6.00	35000	1.00	35000	1.00	35000	Stone Column
7.00	23000	1.00	23000	1.00	23000	Untreated Soil
9.00	35000	1.00	35000	1.00	35000	Untreated Soil

Note:
Stone column diameter = 1000 mm
Stone column depth = 6.0 m below foundation level

VI. ESTIMATED SETTLEMENT OF FOUNDATIONS AFTER SOIL IMPROVEMENT

The estimated settlement of the foundation after soil improvement at the working pressure of 200 kN/m^2 is shown in Table 5.

Table 5 Estimated settlement of the foundation after soil Improvement at working pressure

Serial No.	Footing number	Width m	Length m	Stone column grid	Grid type	Estimated settlement mm
1	F01	1.0	1.0		-	-
2	F02	1.5	1.5	1.5m x 1.5m	Δ	09
3	F02’	1.8	2.50	1.5m x 1.5m	Δ	09
4	F03	3.0	3.0	1.5m x 1.5m	Δ	15
5	F04	3.5	3.5	1.5m x 1.5m	□	18
6	F05	4.0	4.0	1.5m x 1.5m	Δ	18
7	F06	4.5	4.5	1.5m x 1.5m	Δ	20
8	F07	4.8	4.8	1.5m x 1.5m	□	23
9	F08	7.0	8.0	1.5m x 1.5m	□	29
10	F09	8.0	8.0	1.5m x 1.5m	Δ	28
11	F10	5.0	9.6	1.5m x 1.5m	Δ	25
12	F11	5.0	10.0	1.5m x 1.5m	Δ	25
13	F12	7.0	12.0	1.5m x 1.5m	Δ	30
14	F13	5.0	16.4	1.5m x 1.5m	Δ	28
15	F14	4.8	7.01	1.5m x 1.5m	□	25

VII. PLATE LOAD TEST

A load test was performed to verify the requirements set by the geotechnical consultant as shown on Table 6. A third-party neutral investigator is usually invited to perform the plate load test. The test was carried out on four stone columns with footing size 1.5 m × 1.50 m × 0.30 m, according to the recommendations [9].

Table 6 The planning and control components

<table>
<tr><td colspan="5">Allowable bearing capacity = 200 kN/m^2
Maximum test pressure = 1.5 allowable bearing pressure = 300 kN/m^2
Test plate size = 1500 mm x 1500 mm</td></tr>
<tr><td>Percentage of age Load</td><td>Applied pressure kPa</td><td>Applied load KN</td><td>Hydraulic jack pressure Bar</td><td>Minimum time for which load is constant Hour : minute</td></tr>
<tr><td>0</td><td>0</td><td>0</td><td>0</td><td>0:00</td></tr>
<tr><td>10</td><td>20</td><td>45</td><td>10</td><td>0:15</td></tr>
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<tr><td>40</td><td>80</td><td>180</td><td>41</td><td>0:15</td></tr>
<tr><td>50</td><td>100</td><td>225</td><td>51</td><td>0:15</td></tr>
<tr><td>60</td><td>120</td><td>270</td><td>61</td><td>0:15</td></tr>
<tr><td>70</td><td>140</td><td>315</td><td>71</td><td>0:15</td></tr>
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<tr><td>90</td><td>180</td><td>405</td><td>91</td><td>0:15</td></tr>
<tr><td>100</td><td>200</td><td>450</td><td>102</td><td>0:15</td></tr>
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<tr><td>140</td><td>280</td><td>630</td><td>142</td><td>0:15</td></tr>
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<tr><td>0</td><td>0</td><td>0</td><td>0</td><td>1:00</td></tr>
</table>

The footing was loaded according to the configuration shown in Figure (3). The load was applied using a 2×10^6 KN (200-ton) Lukas 2000 hydraulic jack with a piston area equal to 45240 mm^2 reacting against concrete blocks.

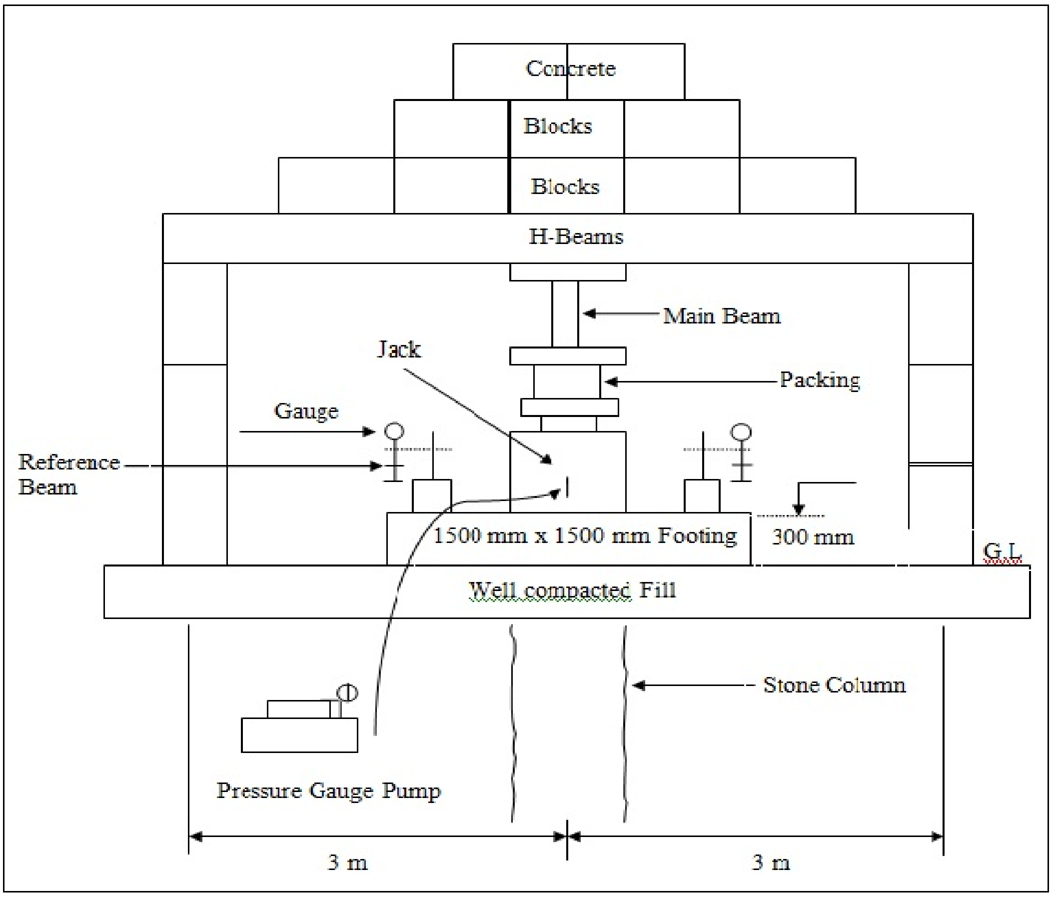

Figure 3 Configuration for loading test

VIII. CONCLUSION REMARKS

The stone columns were constructed to improve the deformation characteristics of the treated soil to reduce primary settlement of the proposed structure. Using the calculated modulus value within a depth of approximately 6 m from the existing grade and the information obtained from the post-improvement CPT test results below approximately 6 m depth, the estimated allowable bearing pressure for the planned shallow foundations of various sizes at the site was obtained. This approach reduced foundation settlement, improved bearing capacity, and hence reduced footing size requirements, which enabled shallow footing construction and stabilization of the slope.

The estimated allowable bearing pressure was taken as the lesser of the two values calculated based on the following:

Settlement considerations as suggested [10], which have been used to calculate the allowable soil bearing pressure for a tolerable total settlement of 25 mm.

Bearing capacity considerations based on the shear strength of the soil as mentioned [11], which have been used within a safety factor of two.

IX. Acknowledgements

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