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AN ALTERNATIVE TO DEEP FOUNDATIONS IN MARGINAL SOILS OF KARACHI

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By

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Abstract

In large cities, such as Karachi, good sites have already been constructed but the demand for new buildings has not ended yet. Builders are forced to build new buildings on sites which have loose and soft soils and generally not considered suitable for the development. The construction of spread footings on loose and soft soils is not feasible due to potential excessive settlement. As an alternative to shallow footings, deep foundations are utilized to transfer load on the suitable soil stratum. Considerable savings in foundation system can be achieved if the bearing capacity of in-situ soil is increased and settlement is reduced.

This paper describes a soil improvement technique, Packed Aggregate Column (PAC), which can be used in large cities of Pakistan such as Karachi where valuable sites have poor to marginal soils. Packed Aggregate Column (PAC) can be used to increase bearing capacity and reduce settlement. The concept of PAC is similar to stone column in which the drilled holes are backfilled with aggregate to support structure. The first step in the construction of PAC is drilling a hole and removing unsuitable soil. In the second step, the hole is backfilled with well-graded aggregate to form high density (packed) aggregate columns. The compaction of aggregate can be achieved using repeated drop of heavy steel weight. Degree of compactness (DC) is defined as a ratio of volume of aggregate to volume of drilled hole. The value of DC for soft soils is higher than the value of DC for stiff soils. The compaction process densifies and forces the aggregates laterally into the side walls of the hole. Temporary casing is used when caving soils and high groundwater table are encountered. Preliminary design methods for PAC are presented in this paper. This paper also discusses the PAC constructability and economics in Pakistan.

1.0 Introduction

The value of land in Karachi and other cosmopolitan cities of Pakistan keep soaring. In the past the development of sites with poor soil conditions was not considered economically feasible but with the increase in land value the sites with poor soil conditions are now often considered economically feasible. However to make poor soil condition sites feasible, engineers are forced to recommend a cost effective foundation system. In Pakistan engineers have limited foundation choices for soft and loose soils sites. Foundation types which are commonly recommended for such sites include deep foundations or mat foundations. An alternative to expensive deep foundation and mat foundation system is in-situ improvement of poor soils. A number of ground improvement techniques, such as stone columns are available that may be used as an alternative to the expensive conventional foundation system. Stone column is one of the ground improvement methods and has a proven record of success in USA. Considering the local conditions of Pakistan, a modified version of stone column ground improvement technology, termed as Packed Aggregate Column (PAC) is introduced in this paper. Packed Aggregate Column (PAC) is ideally suited to reduce excessive settlement and increase bearing capacity of soft clays and silts and loose sands. Settlement of ground improved with PAC can be 30 to 50

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percent of the unimproved ground. PAC for certain sites may be more economical than complete replacement of poor soils and bored or driven piles.

Packed Aggregate Column (PAC) construction involves the partial replacement of poor soils with a compacted vertical column of aggregate. The presence of PAC creates a composite material of high shear strength and low compressibility. The application of PAC is not limited to only increasing bearing capacity and reducing total and differential settlement, PAC can also be used for improving slope stability, increasing the time rate of settlement, and reducing liquefaction potential

This paper presents construction and design process of spread footing on PAC. This paper also provides a cost comparison between PAC and conventional deep foundation system.

2.0 Method of Construction

The construction technique for stone column is well established and routinely used in USA and Europe for stabilization of poor soils. Depending of the method of construction stone columns can be divided into five categories:

1. Vibro-Replacemnet
2. Vibro-Displacemnet
3. Vibro-Concrete Column
4. Rammed Stone Column
5. Rammed Aggregate Piers of Geopiers^{TM}

The construction of stone column using any of the five methods require special tools, which may make stone column soil improvement technique cost prohibitive in Pakistan. Considering the local construction conditions in Pakistan, this paper presents a modified form of stone column that can be constructed using construction equipment commonly used in construction industry of Pakistan. The modified stone column presented in this paper is named "Packed Aggregate Column". The construction of Packed Aggregate Column (PAC) includes the following four steps:

1. A hole is drilled in soil using a drill rig.
2. After drilling hole and using an end dump bucket mounted on a front end loader, a sufficient quantity of gravel is poured at the bottom of the hole to create a 100 to 150 mm (4 to 6-inch) thick layer of gravel at the bottom of the drilled hole. Gradation of aggregate will depend upon the available source of aggregate and subsurface conditions.
3. In the next stage, the gravel layer is compacted. The compaction is accomplished using a steel plate or tamper compactor attached at the end of a hydraulic hammer.
4. Once the bottom layer is compacted, layers of aggregate are then added and compacted until the compacted aggregate reaches the top of the pier. The compacted lift thickness is 300 mm (12-inch) or less. A satisfactory Degree of compactness (DC) defined as a ratio of volume of aggregate to volume of drilled hole is targeted between 120 and 150 percent depending on the soil conditions. For soft soils a higher value of DC is targeted as compare to the DC value for stiff soil. Extra compaction effort should be applied to the first layer of aggregates to fully penetrate the stone and create a large well-compacted base.

The typical diameter and spacing requirements for PAC are the same as for stone columns. Stone column diameter (d_p) typically varies between 0.76 m (2.5 feet) and 1.2 m (4.0

feet). Similar to stone columns, PAC can be installed in triangular, square, or rectangular grid patterns with minimum center to center pier spacing of 305 mm (12-inch) with typical center to center pier spacing of $1d_p$ to $3d_p$. Typical layout of PAC is shown in Figure 1.

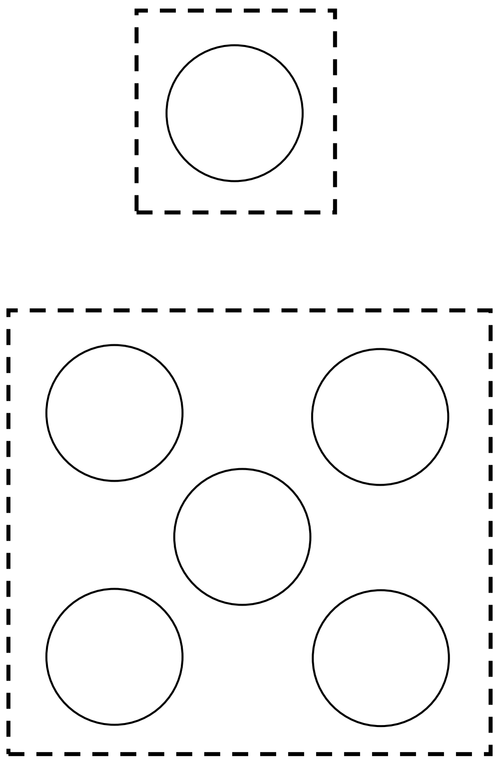


Figure 1: Typical grid pattern for PAC

3.0 Comparison with Stone Column

Due to the use of the similar construction material (rocks, stones, or aggregate) PAC, Geopiers^{TM}, and stone columns formed by vibro-replacement or vibro-displacement method look similar. However, all these soil improvement techniques differ in terms of their method of construction and equipment used for construction. The major differences between PAC, Geopiers^{TM}, and stone columns formed by vibro-replacement or vibro-displacement method are listed below in Table 1:

Table 1: Comparison between stone columns, Geopiers^{TM} and PAC

Stone Column	Rammed Aggregate Pier of Geopiers^{TM}	Packed Aggregate Column (PAC)
Stone columns are constructed either by vibro-replacemnet method or vibro-displacemnet method.	Rammed Aggregate Piers (RAP) of Geopiers^{TM} are excavated rather than displaced by vertical or horizontal vibration.	Similar to RAP of Geopier^{TM}

Stone Column	Rammed Aggregate Pier of Geopiers™	Packed Aggregate Column (PAC)
Stone is densified using a vibrating probe. The term vibroflot or poker is frequently used for the probe.	Stone is densified using a hydraulic hammer and specially designed impact tamper. The impact tamper has 45-degree beveled sides.	Stone is densified using a hydraulic hammer and commonly used steel impact tamper instead of 45-degree beveled side impact tamper.
Stone column completely penetrates the weak strata.	RAP usually does not extend to stronger soil.	Similar to RAP of Geopier™

4.0 Design Procedure

4.1 Area Replacement Ratio

Design procedure for PAC presented in this paper is similar to the design procedure of a stone column. In order to determine the amount of soil replaced by PAC, the area replacement ratio is defined as the ratio of area of pier to the area of total footing.

$$R_a = A_p/A \tag{1}$$

Where: R_a = area replacement ratio,

A_p = area of pier, and

A = footing area.

4.2 Stress Ratio

In order to determine the distribution of stresses between PAC and the surrounding soil matrix, the stress ratio is defined as the ratio of stress in PAC to stress induced in soil matrix.

$$R_s = q_p/q_m \tag{2}$$

Where: R_s = stress ratio,

q_p = stress in pier, and

q_m = stress in soil matrix.

4.3 Settlement Analysis of Soils Improved with PAC

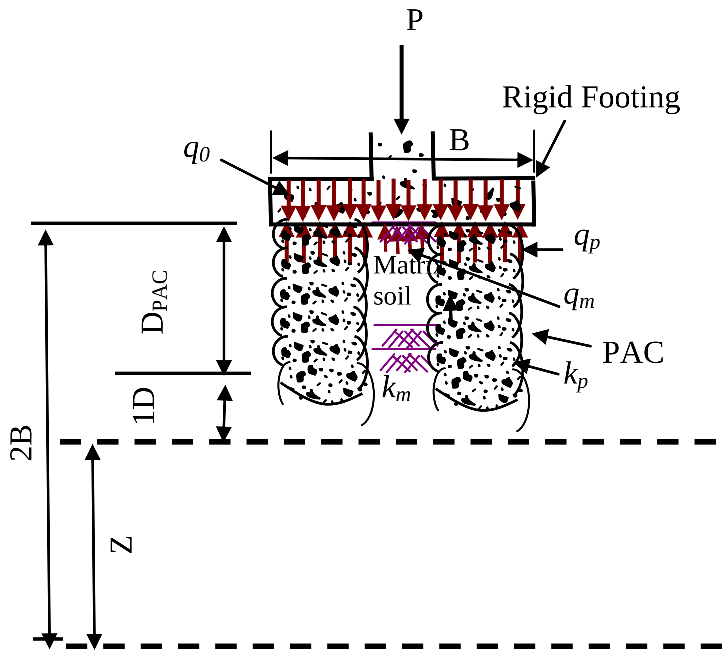
The total settlement of a footing supported on PAC is the sum of the settlement of the PAC reinforced soil and the settlement of soil below the PAC tip. The settlement of the PAC reinforced soil and the settlement of soil below the PAC tip is a result of immediate and consolidation settlement. The equilibrium of vertical forces in Figure 2 gives the following equation.

$$q_0 A = q_p A_p + q_m A_m \tag{3}$$

Where: q_0 = average bearing stress, and

A_m = area of matrix soil

Other terms are the same as defined in equations 1 and 2.



D = Diameter
D_{PAC} = Depth of drilled hole
Z =2B – (1D + D_{PAC})

Figure 2: Stress distribution between PAC and matrix soil for settlement analysis

Equation 3 can be written in terms of R_a and R_s.

$$q_0 = q_p \frac{A_p}{A} + q_m \frac{A_m}{A} \tag{4}$$

From Equation 1

$$q_p = R_s . q_m \tag{5}$$

From Figure 5

$$A_m = A - A_p \tag{6}$$

Using Equations 5 and 6, Equation 4 can be written in the following form,

$$q_0 = R_s q_m R_a + q_m \frac{A - A_p}{A} \tag{7}$$

$$q_0 = R_s q_m R_a + q_m (1 - R_a) \tag{8}$$

$$q_0 = q_m (R_s R_a + 1 - R_a) \tag{9}$$

$$q_0 = q_m\left[R_a(R_s - 1) + 1\right] \tag{10}$$

Solving for q_m,

$$q_m = \frac{q_0}{[R_a(R_s - 1) + 1]} \tag{11}$$

Similarly,

$$q_p = \frac{q_0 R_s}{\left[R_a(R_s - 1) + 1\right]} \tag{12}$$

Subgrade reaction modulus (*k*) is defined as the ratio of applied stress to settlement. Therefore, the subgrade reaction modulus for PAC and the matrix soil can be defined using Equations 13 and 14, respectively.

$$k_p = \frac{q_p}{\delta_p} \tag{13}$$

$$k_m = \frac{q_m}{\delta_m} \tag{14}$$

Due to displacement compatibility at the base of the footing, settlement of the footing (δ), settlement of the PAC (δ_p), and the settlement of the matrix soil (δ_m) should be equal. Therefore,

$$\delta = \delta_p = \delta_m$$

or we can write:

$$\delta = \frac{q_p}{k_p} = \frac{q_m}{k_m} \tag{15}$$

The settlement of the soil below the PAC and the consolidation settlement can be computed using the conventional geotechnical analysis. The footing stresses in the soil below the PAC are computed using Westergaard or Boussinesq analysis. The computed footing stresses in the soil below the PAC are used for the settlement of soil below the PAC.

4.4 Bearing Capacity Analysis of Soils Improved with PAC

Failure mechanisms similar to stone columns as listed by Elias et. al. (2001) and Barksdale and Bachus (1983) are possible for PAC. Particularly bulging of a PAC is a major concerned in low shear strength soil. The bulging of a PAC occurs when the lateral stresses caused by PAC exceeds the lateral resistance of the surrounding matrix soil (Figure 3). The lateral stresses are low at the top of the PAC where the overburden stresses are the lowest. Bulging generally occurs in a zone extending from the top of the pier to the depth of 2 to 3 times the diameter of the pier. Gibson and Anderson (1961) found the following closed form solution for a cylindrical expansion cavity in an elasto-plastic material.

$$\sigma_3 = \sigma_{r0} + s_u \left[1 + \ln \left\{ \frac{E_u}{2s_u(1+\mu)} \right\} \right] \quad (16)$$

Where:

σ_3 = the ultimate total lateral stress

σ_{ro} = initial total in-situ lateral stress

s_u = undrained shear strength of the matrix soil,

E_u =undrained modulus of the matrix soil, and

μ = Poisson's ratio of the matrix soil.

$$\sigma_{r0} = \sigma_{v0} k_{p,m} \quad (17)$$

Where:

σ_{vo} = effective vertical stress

$K_{p,m}$ = Rankine's passive lateral earth pressure for the matrix soil.

The maximum load that may be applied at the top of the PAC without causing bulging failure can be estimated using the following equation:

$$q_{ult,p} = \sigma_3 k_p \quad (18)$$

Where, $k_p = \tan^2(45 + \varphi_p/2)$ **and** φ_p is the angle of internal friction of the pier material.

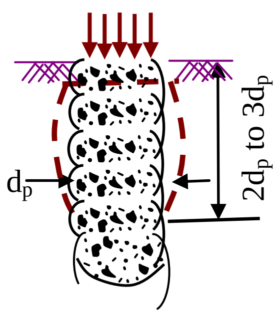


Figure 3: A Possible mode of bulging failure of a single PAC

The bearing capacity of the tip of the PAC can be computed using the Terzaghi bearing capacity equation.

$$q_{tip,p} = cN_c + \sigma_v' N_q + 0.5 d_{shaft} \gamma N_\gamma \quad (19)$$

Where:

N_c, N_q, and N_γ = dimensionless bearing capacity factors,

γ = unit weight of matrix soil unit weight, and

σ_v' = overburden stress at the elevation of the tip of the PAC

For cohesionless soil:

$$f_s = k_p \sigma_v^{'} \tan\varphi_m^{'} \tag{20}$$

Where:

f_s = unit resistance

k_p = Rankine's passive earth pressure coefficient

$\sigma_v^{'}$ = overburden stress

φ_m = friction angle of the matrix soil.

For cohesive:

$$f_s = s_u$$

Where:

s_u = undrained shear strength of matrix soil

4.5 Lateral Capacity of PAC

The sliding resistance provided by PAC can be computed using the following equation:

$$\sigma_{l,p} = q_p \tan\varphi_p^{'} \tag{21}$$

The sliding resistance provided by matrix soil can be computed using the following equation:

$$\sigma_{l,m} = q_m \tan\varphi_m^{'} + c_m \tag{22}$$

The values of q_m and q_p are given by Equations 11 and 12, respectively.

Where:

$\sigma_{l,p}$ = sliding resistance provided by PAC

$\sigma_{l,m}$ = sliding resistance provided by matrix soil

All other parameters used in equations 21 and 22 are the same as defined previously.

The passive pressure developed in front of the footing in the matrix soil can be computed by the following equation (Das 1999):

$$\sigma_p = 1/2\gamma D_f^2 k_p + 2cD_f\sqrt{k_p} \tag{23}$$

The passive force (F_p) can be calculated by multiplying the passive pressure with the width of the footing (B).

$$F_p = \sigma_p B \tag{24}$$

Where:

D_f = depth of footing below the ground surface.

All other parameters used in equation 23 and 24 are the same as defined previously.

A factor of safety generally between 1.5 and 2 is used to calculate the allowable lateral resistance.

A factor of safety 1.5 to 2 is typically used for settlement, bearing capacity, uplift capacity, and lateral capacity calculations.

4.6 Seismic Site Classification for Soils Improved with PAC

Similar to composite friction angle and cohesion, the composite shear wave velocity can be calculated using the following equation (Miller, J. et al. 2004).

$$\upsilon_{m,comp} = (R_a)\upsilon_p + (1 - R_a)\upsilon_m \tag{25}$$

Where:

$\upsilon_{m,comp}$ = shear wave velocity of PAC reinforced zone,

υ_p = shear wave velocity of PAC,

υ_m = shear wave velocity of surrounding matrix soil, and

R_a = area replacement ration as defined by Equation 1

A shear wave velocity of 365 m/sec (1200 ft/sec) is typically used for Geopiers™ (Miller, J. et al. 2004), considering the construction material is the same for Geopiers™ and PAC, the same range can be used for PAC until the actual shear wave velocity data for PAC is available. The shear wave velocity may be calculated using shear modulus and unit weight of soil.

$$\upsilon_s = (G/\rho)^{0.5} \tag{26}$$

Where:

G = shear modulus

ρ = unit weight of soil (density divided by gravitational coefficient 9.81 m/sec^2 or 32.2 ft/sec^2)

The shear modulus may be measured in the field and can be estimated form the following correlation (Miller, J. et al. 2004):

$$G_{\max} = 20{,}000(N1)_{60}^{0.333}(\sigma_m^{'})^{0.5} \tag{27}$$

Where:

$(N1)_{60}$ = SPT N-value corrected for energy and overburden

$\sigma_m^{'}$ = mean effective stress

5.0 Determination of Primary Parameters for Design of PAC Supported Footing

The subgrade modulus of PAC (k_p) and the allowable bearing capacity (q_c) are two primary parameters required for the design of footing supported on PAC. For preliminary design, these parameters can be determined using SPT N-value or undrained shear strength (s_u).

The preliminary design values assumed for the design should be verified with full-scale modulus load test. The purpose of the modulus test is to measure the PAC stiffness value k_p. The modulus test should be performed in accordance with Standard Test Methods for Deep Foundations under Static Axial Compressive Load (ASTM D 1143). The PAC should be loaded to 150 percent of its maximum design load to measure the stiffness modulus and then loaded to 200 percent of the design load to measure ultimate capacity.

Subgrade modulus for matrix soil (k_m) also determined using the static load test or estimated from subsurface information obtained from test borings completed at the site.

Full scale direct shear tests conducted on 0.6 m (30-inch) diameter RAP of Geopier™ and small scale laboratory tests conducted on reconstituted samples of RAP aggregates indicated the angle of internal friction angle of RAP aggregate between 49 and 53 degrees depending on the gradation (Wissmann et al. 2001).

Typical value of stress ratio R_s for vibro-displacement or vibro-replacement stone columns is generally between 2.5 and 5. However, typical value of stress ratio R_s for Geopier™ is generally between 8 and 32 (Fox and Cowell, 1998). At the time of writing this paper no data is available for stress ratio for PAC, however it is expected that PAC will have considerably higher stress ratio than the vibro-displacement or vibro-replacement stone columns due to the ramming effect. For preliminary design of PAC, a R_s value of 8 may be assumed.

As mentioned earlier, the construction of PAC does not require any special construction equipment and the construction of PAC can be achieved using commonly available construction equipment. However, it will be necessary to perform a full scale load test on each site where PAC is going to be used. Full scale load test should be a compulsory requirement for each project utilizing PAC until sufficient load test data is available for different soils typically encountered in Pakistan.

6.0 Cost Comparison of PAC with Deep Foundation

PAC can be an economical alternative to over-excavation and replacement and to deep foundations. PAC supported foundations cost can be 20 to 50 percent less than traditional deep foundations. In order to compare the cost of PAC foundation option with a deep foundation, a hypothetical foundation plan (Figure 4) is used.

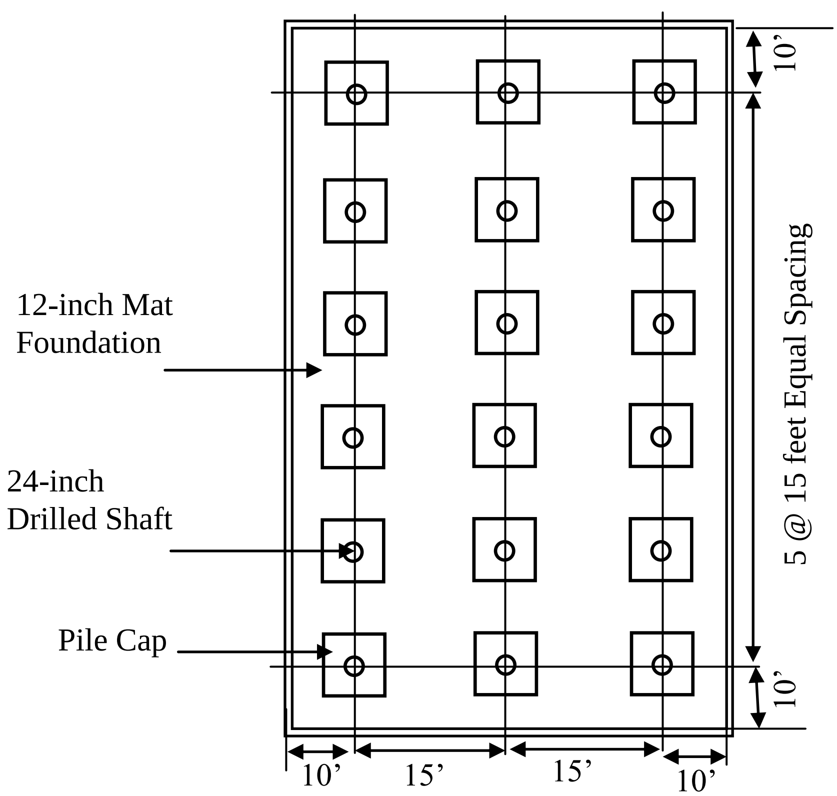


Figure 4: Foundation plan for cost analysis

For 355 kN (40 ton) load, a 0.41 to 0.61m (16 to 24-inch) diameter and 12 to 15 m (40 to 50 feet) deep pile approximately costs 100,000 Pakistani Rupees (Rs) or approximately $1000 per pile (1 dollar is assumed approximately 100 Rs). The cost of concrete and steel for the construction of the pile is approximately Rs.60,000 ($600). The following Table 2 shows a cost analysis of 0.9 m (36-inch) diameter and 4.5 m (15 feet) deep PAC.

Table 2: Cost Analysis of a single PAC

Item	Unit Rate (Rs)	Total Cost (Rs)
Drilling	3000 per foot	15 feet * 3000 = 45,000
Aggregate	40 per cu. foot	$\pi/4*(3)^2*(15)*40 = 4{,}241$

Assuming the mobilization cost and labor for the construction of PAC will be the same as for the deep foundation. Further, assuming the spread footing will cost approximately the same as the cost of pile cap. The drilling and aggregate cost of a 0.9 m (36-inch) diameter PAC will be approximately Rs.50,000 ($500), which is approximately 20 percent less than the cost of material of a pile foundation. For a foundation plan shown in Figure 4, the pile foundation will cost approximately Rs.1080,000 ($10,800) on the other hand the PAC will cost approximately Rs.900,000 ($ =9,000), the saving in the foundation will be Rs.180,000 ($1,800). As a general rule, PAC will provide the most saving in a situation when deep foundations are more than 9 or 12 m (30 or 40 feet) deep. The actual cost of PAC will also depend on the subsurface conditions.

7.0 Summary and Conclusions

Packed Aggregate Column (PAC) can be used as an alternative to deep foundation and mat foundation system. PAC is one of the ground improvement methods and is a slightly modified form of conventional stone columns. PAC ground improvement technology is ideally suited for soft clays and silts and also loose sands. The construction of PAC involves the partial replacement of poor soils with a compacted vertical column of aggregate. The presence of PAC creates a composite material of high shear strength and low compressibility. PAC for certain sites may be more economical than complete replacement of poor soils and bored or driven piles. Settlement of ground improved with PAC is believed to be 30 to 50 percent of the unimproved ground. A full scale load test should be a compulsory requirement for each project utilizing PAC until sufficient load test data is available for different soils typically encountered in Pakistan. The number of load tests to verify workmanship and design assumptions will depend upon the subsurface conditions and the size and importance of the project. A preliminary cost comparison presented in this paper indicate that use of PAC resulted in cost savings with the same performance as the other conventional foundation system.

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