INTERFERENCE EFFECT OF TWO CLOSELY SPACED FOOTINGS ON BIO-SILICIFIED SAND

C.J. Ragiya\textsuperscript{1}, K. Salinitha\textsuperscript{2}

ABSTRACT

Industrialization and urbanization has led to situations where footings of same or adjacent structures come closer. This will lead to change in the bearing capacity and load settlement behaviour of the isolated footings due to interference of influence zone of footings. The designer should be aware of this interference effect on the load settlement behavior of footing. Therefore, the problem of interaction between adjacent footings is of great practical significance. The conventional solutions of bearing capacity and settlement of soil under shallow foundations do not consider footings interactions. In this paper, laboratory model tests were conducted to study the effect of interference on the load settlement behaviour of two closely spaced strip footings resting on medium dense sand subjected to static load. The influence of spacing between the footings on their load settlement characteristics was investigated by varying the spacing as 0.14B, 1B, 2B, 4B and 6B (B is width of the strip footing). Effectiveness of ground improvement technique to reduce the interference effect of such closely spaced footing was also studied. Experimental setup with small scale steel strip footings of size 36cm x 7cm x 2cm was used for the studies. Footings were carrying exactly equal loads applied through hydraulic jack under a reaction beam. Ground improvement technique chosen for the study was a new method of grouting called biologically inspired silicification process. This process offers environmental and physical advantages over traditional sodium silicate grout.

To determine the concentration of sodium silicate at which the dense sand obtained the maximum compressive strength, unconfined compressive strength tests were carried out on sand treated with different concentrations of sodium silicate (0%, 10%, 20%, 30%, 40%, 50% and 60%). It was seen that 40% of sodium silicate concentration gave the maximum compressive strength to the dense sand. Tests were conducted on using 3 types of cationic polyelectrolyte (Floquat 3249, Floquat 4440 and Floquat 4420) at different concentrations (0%, 5%, 15%, 25%, 35%, and 45%) in combination with the optimum concentration of sodium silicate. Influence of bio-silicification on medium dense sand on the interference
Effect of strip footings placed at optimum spacing was studied by comparing its load settlement characteristics with that of strip footings placed un-grouted sand. From the study, it was found that bearing capacity of un-grouted sand is maximum at a clear spacing of 1B between the footings. It was also seen that interference effect causes a 37.5% percentage increase in bearing capacity of the two closely spaced footings as compared with bearing capacity of isolated footing. Settlement behavior of the footing was also influenced by the interference effect. Sand pretreated with 25% solution of cationic polyelectrolyte (Floquat) and followed by 40% solution of sodium silicate grouting shows 100 to 520% increase in compressive strength than the traditional sodium silicate grout mixtures without any pretreatments. Sand pretreated with Floquat 4440 and Floquat 4420 have more compressive strength than Floquat 3249. Sand pretreated with Floquat 3249 has only slight increase in compressive strength than traditional sodium silicate grouting. Interference effect is less significant on sodium silicate grouted sand.

Keywords: Ground improvement, Floquat, Footings, Interference effect, Bio-silicification, Sodium silicate grouting.

C.J. Ragiya, M.Tech. Student, Civil Engg. Dept., IES College of Engg., Thrissur, Kerala, ragiyajose@gmail.com
K. Salinitha, Asst. Professor, Civil Engg. Dept., IES College of Engg., Thrissur, Kerala, salinithak@gmail.com.
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C. J. Ragiya, M.Tech. Student, IES College of Engg., Thrissur, Kerala, ragiyajose@gmail.com
K. Salinitha, Asst. Professor, IES College of Engg., Thrissur, Kerala, salinithak@gmail.com

ABSTRACT: Laboratory model tests were conducted to study the interference effect of two strip footings resting on medium dense sand subjected to static load. The influence of spacing between footings and effectiveness of grouting were studied. Ground improvement technique chosen was a new method of grouting called bio-silicification process. From the study, it was found that load carrying capacity of interfering footing is higher than that of isolated footing and is maximum at a clear spacing of 1B between footings. Bio-silicification process for grouting shows large increase in strength than the control sodium silicate grouting. Interference effect is less significant on grouted sand.

INTRODUCTION
Thickly populated urban areas compel the buildings to be placed very close to each other. Design of foundation of structures is made with due care of the loads coming in the building. But there could be variation in the load carrying capacity of the closely situated footings of adjacent buildings. Engineers have to consider footing interactions in such situations. The problem of interaction between adjacent footings is of great practical significance. According to the footing failure mechanism given by Terzaghi, the passive zone extends laterally to three to five times the footing width. So the footing will behave as an individual single footing only beyond this lateral distance. If footings are placed within this lateral distance, then its load carrying capacity, failure and slip mechanism will no longer be that of a single footing [12,10]. These changes are due to interference of failure zone of loaded footings.

Interference effect of strip footing is more dominant than other types of footings and this is more significant in sandy soil than clay soil [14, 3]. The conventional solutions of bearing capacity and settlement of soil under shallow foundations did not consider footings interaction. The famous equations of bearing capacity by Terzaghi (1943) and Meyerhof (1951) also did not consider the effect of interference between adjacent footings [4, 17]. In this paper, laboratory model tests were conducted to study the interference effect of two strip footings resting on medium dense sand subjected to static load.

Biologically inspired silicification process is a new kind of cementation method used to improve the strength of the soil [8]. In this method, soil is pre-treated with a commercially available cationic poly-electrolyte before sodium silicate grouting. Bio-silicified sand shows more strength and stiffness and it has environmental and physical advantages over traditional sodium silicate grout mixtures.

Most earth materials have a negative charge on their surface. In biologically inspired silicification process, saturated soil is pre-treating with cationic poly-electrolyte. This compound should offer a positively charged surface to the grains by putting a high concentration of positive charges on to it. Poly electrolytes are members of a broad class of organic compounds that can serve as growth factors. This sets the stage for extensive silica
nucleation and polymerization. Physical model of silicification process can be made using a simple sand assemblage as shown in the schematic representation given in the figure 1 below.

![Fig. 1 Schematic representation of silicification process](image)

Sodium silicate is introduced in specific concentrations to cause grain to grain silica polymerizations after pre-treatment. This will produce a strengthened material and resulting in cement filling the voids and coating the grains. Interference effect of footings on grouted sand is also studied in this paper by conducting a series of laboratory model tests.

**PROBLEM DEFINITION**

Schematic diagram of laboratory test setup is shown in the figure 2 given below.

![Fig. 2 Schematic representation of test setup](image)

Equal load, ‘P_u’ is applied symmetrically over strip footings. ‘B’ is the width of the footings and ‘S’ is the clear spacing between footings. Footings were placed over sand mass of depth, ‘d’.

**MATERIALS AND PROPERTIES**

In this experimental work, a rectangular steel tank of size 1.65 m (length) x 0.37 m (width) x 0.65 m (depth) was used. Steel tank is properly stiffened using steel angles to withstand the loads without bending. Dimensions of strip footings were fixed by reviewing the research papers. Two steel footings of size 36 cm (length) x 7 cm (width) x 2 cm (thickness) were used as model strip footings.

Sand was collected from Pattambi region of Palakkad district in Kerala. Dry sieve analysis was conducted as per IS 2720: Part 4: 1985 and the grain size distribution curve for the soil were plotted as shown in figure 3 given below.

![Fig.3 Particle size distribution curve](image)

From the graph, it can be seen that the gradation of the soil is Poorly Graded (SP). The uniformity coefficient and coefficient of curvature was found out from the D_{30} and D_{60} values obtained from the particle size distribution curve.

The properties of sand obtained by conducting various laboratory tests confirming to the corresponding IS codes are given in the table 1 given below.
The obtained values of coefficient of curvature and uniformity coefficient confirm the gradation of soil as poorly graded.

Sodium silicate for chemical grouting has a weight ratio of 3.22:1(SiO$_2$: Na$_2$O) and specific gravity of 2.61. It is white to greenish aqueous solution that is readily soluble in water. It is basically an alkaline solution and on acidification it will start polymerization to form a silica gel which is hard and glossy.

Three types of cationic poly-electrolytes (Floquat 4440, Floquat 4420, and Floquat 3249) were used in this study. The basic properties as given by the manufacturer are given in the table 2 given below.

<table>
<thead>
<tr>
<th>Name</th>
<th>Monomer type</th>
<th>Concentration in water</th>
<th>Viscosity (m$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fl 4420</td>
<td>Medium molecular weight polydadmac</td>
<td>20%</td>
<td>80-180</td>
</tr>
<tr>
<td>Fl 4440</td>
<td>Medium molecular weight polydadmac</td>
<td>40%</td>
<td>1000 - 3000</td>
</tr>
<tr>
<td>Fl 3249</td>
<td>High molecular weight epiDMA copolymer (polyamine)</td>
<td>20%</td>
<td>4000 - 9000</td>
</tr>
</tbody>
</table>

Each compound is made of different monomers and they show different viscosities. Buffer solution of citric acid of pH 4 was purchased from E. Merck Limited. Sodium silicate is basically alkaline in nature. Small quantity of buffer solution will acidify the sodium silicate to weak acidic level and enhance polymerization of the sodium silicate grout.

**METHODOLOGY**

**Experimental Modelling**
Sand was filled in the tank in 10 layers of equal thickness to a height of 50 cm. Quantity of sand in each layer, corresponding to the required relative density chosen for the study was calculated. Each layer of sand was filled in the tank carefully by compacting so as to achieve the required density. Footings were placed over sand in the tank as shown in the schematic diagram given in Fig.2. It was placed at proper locations using plumb bob and levelled using spirit levels to avoid eccentric loading. Hydraulic jack was installed vertically
between footings and reaction beam. Vertical loading shaft was installed between footings and proving ring to transfer the load properly. A horizontal loading ram was placed above footings to transfer the load symmetrically, in case of two symmetrically loaded footings. Load applied on the horizontal beam was transferred symmetrically to the two footings, as point load. The entire experimental setup is shown in the figure 4 given below.

![Experimental setup](image)

**Fig. 4** Experimental setup

A proving ring of 50 kN capacity was placed between the hydraulic jack and footings to monitor the applied load. Two dial gauges of 25 mm capacity were placed in either sides of the footing to monitor the settlement of footing during loading, which firmly fixed on the side walls of the tank. Load was applied using a hand operated hydraulic pumping system.

A series of load deformation tests as per IS codes (IS 1882: 1982) were conducted. Each load increment was applied using hydraulic jack and corresponding settlements were measured from dial gauges.

Tests were continued until shear failure of the footings. A clear general shear failure pattern was visible with heaves on both sides. Slight downward movement of footings and development of fully plastic shear zones with heaves confirmed that it was a general shear failure.

**Determination of Optimum Grout Concentration**

Separate stock, pre-treatment, and sodium silicate solutions were prepared. Stock solution of each poly-electrolyte was prepared by mixing 10 g of each poly-electrolyte in 500 ml de-ionized water. These stock solutions were then diluted with de-ionized water to produce different concentrations (5%, 15%, 25%, 35%, and 45%) of pre-treatment solutions (in 5% solution, 100 ml pre-treatment solution contains 5 ml stock solution and 95 ml de-ionized water).

Different concentrations (10%, 20%, 30%, 40%, 50%, and 60%) of sodium silicate solutions were prepared by mixing the sodium silicate solution in de-ionized water. Buffer solution of citric acid was added to sodium silicate solutions to weakly acidify the solutions.

Un-confined compression strength tests on grouted specimens were used to evaluate effectiveness of sodium silicate and poly-electrolyte and to obtain optimum concentration of this grouting solution that has high strength and stiffness. U.C.C split moulds of 50 mm diameter and 100 mm height were used. Sand was filled in the mould at a density of 85% to make the comparison more clear. Schematic setup of grouting setup is shown in the figure 5 given below.

![Grouting setup](image)

**Fig. 5** Schematic representation of grouting setup
Sodium silicate solution, pre-treatment solution and de-ionized water were kept in three different reservoirs. Solutions were injected under gravity without any external pressure one by one.

Tubes were connected from the bottom of reservoirs to the bottom end cap of U. C.C mould. Flow of solutions was upward from the bottom of the mould to top of the mould to get a uniformly grouted sand specimen. A waste line was connected at the top. The head difference rapidly decreased from a maximum of approximately 0.3 m at the start of injection to zero at the end of the injection. Specimen was saturated subsequently with de-ionized water, pre-treatment solution and sodium silicate – buffer solution. Samples were allowed to air dry for 7 days. Unconfined compression tests were conducted on these prepared specimens as per IS code provisions. The specimen was compressed until the failure surface was definitely developed.

**Grouting and Testing in Tank**

Pressure grouting was done in test tank at three points as per IS 4999 – 1991. A pressure grouting equipment was used for grouting of the sand filled in the test tank. This equipment consists of a tank, mixing system, and pressure applying system. Complete grouting system is shown in the figure 6 given below.

Grout was filled in equipment through inlet pipe provided on the tank. Filled grout was mixed thoroughly using the agitator and motor system. Pressure rose in tank using hand operated pump and opened the outlet valve which forced the grout into the holes provided on the tube inserted in the soil. Holes are provided all over in the tube inserted in the tank. Grouted sand in the tank was allowed to air dry for 7 days. After a drying period of 7 days, load tests were conducted as per IS code specifications. Test continued till failure and load – settlement plots were prepared. Clear failure planes as cracks were visible.

**RESULTS**

**Interference Effect on Load Settlement Behaviour of Single Strip Footing Placed on un-grouted Sand**

Laboratory load tests were conducted on single strip footing and two strip footings placed at clear spacing, S. Spacing between the footings was varied as 0.14B, 1B, 2B, 4B and 6B, (where B is the width of footings). Load settlement behaviour of strip footing at various spacing resting on sand with relative density 67% is shown in the figure 7 given below.

![Fig. 6 Grouting in test tank](image)

From the load settlement plot, it is clear that bearing capacity of interfering strip footing at all spacing is greater than that of isolated footing. At a
clear spacing of 0.14B between footings, both bearing capacity and settlement values have shown tremendous increase. At spacing 1B between footings bearing capacity of strip footing is maximum and settlement is minimum. Beyond spacing 1B, with increase in spacing, bearing capacity and settlement decreases. It can be seen that, isolated strip footings has low bearing capacity values compared to the strip footings placed at critical spacing of 1B.

Interference of influence zones at spacing 1B would lead to 37% increase in load carrying capacity. Settlement is maximum at spacing 0.14B between strip footings. With higher spacing, settlement of strip footings is similar to single isolated strip footings. Settlement decreases with increasing spacing, but it is least at critical spacing 1B.

**Influence of Silicate Content on the Stress Strain Behaviour of Sand**

Unconfined compression tests were conducted in sand with different concentrations of sodium silicate solutions (10%, 20%, 30%, 40%, 50%, and 60%). The stress-strain behaviour of the sodium silicate grouted sand is given in the figure 8 below.

![Fig. 8 Stress strain behaviour at different silicate content](image)

From the plot it can be seen that strength is maximum at 40% silicate solution. Variation in unconfined compressive strength of sodium silicate grouted sand is shown in the figure 9.

![Fig. 9 U.C.C strength at different silicate concentration](image)

From the above graph, it is observed that unconfined compressive strength of sodium silicate grouted sand has increased up to 40% concentration of sodium silicate. On further, increase in concentration, the strength has decreased. This is because as the concentration of sodium silicate grout is more than 40%, the viscosity of the grout increases which in turn inhibits the penetration of the grout into finer pores of sand.

**Influence of Floquat Concentration on Stress Strain Behaviour of Sodium Silicate Grouted Sand**

Axial – stress strain plots of U.C.C tests of sand specimen pretreated with Floquat 4440 at different concentrations (5%, 15%, 25%, 35%, and 45%) in combination with optimum concentration of sodium silicate solutions (40%) were given in figure 10 below.

![Fig. 10 Axial stress strain graph at different FL 4440 content](image)
From the graph, it can be seen that sample pre-
treated with 25% concentration of Floquat 4440
and 40% sodium silicate solution has maximum
strength. Results of the unconfined compression
strength tests conducted using different percentage
of Floquat 4420 in combination with 40% sodium
silicate is shown in the figure 11 given below.

![Axial stress strain graph at different FL 4420 content](image1)

**Fig. 11** Axial stress strain graph at different FL 4420 content

From the graph it can be seen that FL 4420’s
concentration of 25% in combination with 40% sodium silicate achieves maximum strength. Behaviour is similar to that using FL 4440. Stress strain behaviour of sand treated with different concentrations of FL 3249 in combination with 40% sodium silicate solution is shown in figure 12 given below.

![Axial stress strain graph at different FL 3249 content](image2)

**Fig. 12** Axial stress strain graph at different FL 3249 content

From the graph given in figure 11, it can be seen that 15% of FL 3249 in combination with 40% sodium silicate has maximum strength.

Lower concentrations of polyelectrolyte improve
cementation whereas high levels of polyelectrolyte appear to remove silica from solution by adsorption which reduces the amount of silica available for grain to grain bonding. Un-confined compressive strength values obtained for all types of floquats at different concentrations, in combination with 40% sodium silicate is shown in the figure 13 given below.

![U.C.C Strengths at different FL concentrations](image3)

**Fig. 13** U.C.C Strengths at different FL concentrations

At all Floquat concentrations, strength of sand due
to pre-treatment using Floquat is more than the strength of sand with sodium silicate grouting without pre-treatment. From the graph given in the figure 12, it can be seen that the type and concentration of polyelectrolyte influenced the mechanical performance of the cemented sand.

Floquat 4420 has maximum increase of 519% when pre-treated with 25% solution of Floquat. And Floquat 4440 has a maximum increase of 376% when pre-treating with 25% solution of Floquat. Whereas Floquat 3249 has a maximum increase of 106% only, when pre-treating with 15% solution of Floquat.

Sand pretreated with Floquat 3249 has only slight increase in compressive strength than traditional sodium silicate grouting. Sand pretreated with
Floquat 4440 and Floquat 4420 have more compressive strength than Floquat 3249. Pre-treating with cationic poly-electrolyte has increased the strength than conventional grouting. Increase in strength is maximum for Floquat 4420 at 25% solution.

It can be concluded that optimum concentration for bio-silicification process is pre-treating sand with 25% solution of FL 4420 followed by grouting with 40% sodium silicate and buffer solution.

**Conclusions**

Floquat 4440 and Floquat 4420 have more compressive strength than Floquat 3249. Pre-treating with cationic poly-electrolyte has increased the strength than conventional grouting. Increase in strength is maximum for Floquat 4420 at 25% solution.

It can be concluded that optimum concentration for bio-silicification process is pre-treating sand with 25% solution of FL 4420 followed by grouting with 40% sodium silicate and buffer solution.

**Effect of Spacing between Footings on Load Settlement Behaviour of Interfering Footings, Placed on Reinforced Soil**

Obtained load deformation behaviour of interfering strip footings (placed at critical spacing) and single strip footing placed on grouted sand was compared and that is shown in the figure 14 given below.

![Figure 14](image.png)

Fig. 14 Behaviour of interfering strip footing at clear spacing of 1B on grouted sand

There is a 5.77% increase in load carrying capacity of interfering strip footings placed on grouted sand than that of isolated strip footing on grouted sand. But this increase in load carrying capacity due to interference effect is less than that of footings placed on non-grouted sand.

Load carrying capacity of single strip footing is increased by 139.9% through grouting using bio-silicification process. Slight increase in settlement was also observed in grouted sand. Load carrying capacity of interfering strip footing placed at critical spacing was increased by 84.5% through grouting using bio-silicification process.

Interference effect has less influence on sodium silicate grouted sand.

**CONCLUSIONS**

Major conclusions that obtained through discussing the results of the thesis work are given below

1. If the passive shear zones of adjacent footings interfere with each other then the load settlement behaviour of footing will change due to interference effect.
2. Load settlement behaviour of interfering footing depends on the spacing between the footings. Load carrying capacity of interfering footing attains a peak maximum value at a clear spacing 1B. Load carrying capacity of interfering footings is always higher than that of single isolated footing.
   - Footings which are placed at a clear spacing of 1B on sand of 67% density, shows 37.5% increase in load carrying capacity when compared with the single isolated footing.
3. When clear spacing between footings is more than 1B, load carrying capacity of interfering footing decreases. It behaves like a single isolated footing at a clear spacing of 6B, because there is no interaction of shear zones of footings.
4. Settlement at failure of interfering footing is maximum when footings are closer (that is S = 0.14B).
5. Strength of sodium silicate grouted sand is maximum at 40% solution because more sodium silicate content will increase the viscosity of grout and inhibits the penetration of the grout into finer pores.
6. Introduction of Floquat before sodium silicate grouting will lead to increase the unconfined compressive strength of grouted sand. And un-confined compressive strength of grout ed sand depends on type and concentration of Floquat (FL).
   - FL 4440 shows maximum increase in strength of 375%, at 25% solution of Floquat in combination.
with 40% solution of sodium silicate.
- FL 4420 shows maximum increase in strength of 519.4%, at 25% solution of Floquat in combination with 40% solution of sodium silicate.
- FL 3249 shows maximum increase in strength of 106.1%, at 25% solution of Floquat in combination with 40% solution of sodium silicate.

7. Optimum concentration of grout that has maximum strength can be obtained by pre-treating the 40% solution of sodium silicate grouted sand with 25% solution of FL 4420.

8. Low concentrations of polyelectrolyte improve cementation whereas high levels of polyelectrolyte appear to remove silica from solution by adsorption which reduces the amount of silica available for grain to grain bonding.

9. Load carrying capacity of single isolated footing was found to be increased by 139.9% after grouting the soil. Interfering footing placed at critical spacing of 1B between footings shows 84.5% increase in load carrying capacity after grouting.

10. Footings placed at critical spacing on grouted sand shows 5.76% increase in load carrying capacity due to interference effect. Whereas footings placed at critical spacing on un-grouted sand shows 37.5% increase in load carrying capacity due to interference effect. That is interference effect of footings on grouted sand is less significant than that of on un-grouted sand.

REFERENCES


