

Effect of Column Spacing and Dry Xanthan Gum Content on the Bearing Response of Soft Clay Improved with Sand Columns

Malak Jamal Yahya *, Mohammed Y. Fattah , Mohammed F. Aswad 

Highways and Geotechnical Engineering Department, College of Civil Engineering, University of Technology, Baghdad, Iraq

ABSTRACT

Soft clay foundations commonly exhibit low bearing resistance and excessive settlement, while granular-column performance depends on both column geometry and infill properties. This study experimentally investigates the combined influence of column spacing and dry-blended xanthan gum (XG) content on the bearing response of soft clay improved with a 50 mm sand cushion and a 4 × 4 group of sand columns. Tests were conducted in a 700 × 700 × 800 mm rigid steel box using a 60 × 60 mm square footing. The clay was prepared at a target water content of approximately 25% and an undrained shear strength of approximately 17 kPa. Sixteen sand columns, 25 mm in diameter and 150 mm long, were installed at clear spacings of 20 and 35 mm, corresponding to S_c/d ratios of 1.80 and 2.40. XG contents of 0%, 0.5%, 1%, and 2% by dry sand mass were examined after three days of covered conditioning. Responses were compared at $s/B = 11\%$. Untreated clay carried 98.24 kPa, while the sand cushion increased the pressure to 110.76 kPa. The highest response occurred at 35 mm spacing with 1% XG, reaching 174.15 kPa and $BCR = 1.773$. At 20 mm spacing, the best response occurred with 2% XG, reaching 129.09 kPa and $BCR = 1.314$. The results indicate a non-monotonic spacing-XG interaction, showing that spacing and XG content should be evaluated jointly. The best-performing tested configuration remains specific to the model conditions and requires confirmation through replicated and larger-scale testing.

Keywords: Soft clay, Sand columns, Xanthan gum, Column spacing, Bearing response, Ground improvement.

1. INTRODUCTION

The foundation on soft clay is often subjected to excessive settlement and poor bearing capacity due to the transmission of applied structural loads through a low-stiffness and low undrained shear strength soil mass. The granular columns are effective in improving the behavior of soft clay by introducing relatively stiff and frictional inclusions to enable the transmission of loads, provide resistance against the displacement of the columns, and

*Corresponding author

Peer review under the responsibility of University of Baghdad.

<https://doi.org/10.31026/j.eng.2026.10.02>



This is an open access article under the CC BY 4 license (<http://creativecommons.org/licenses/by/4.0/>).

Article received: 23/05/2026

Article revised: 25/08/2026

Article accepted: 25/08/2026

Article published: 01/10/2026



provide lateral confinement (**Al-Kaisi and Ali, 2013; Andreou et al., 2008; Stuedlein and Holtz, 2013**). Their performance, however, is governed by the composite behavior of the column–soil system rather than by the granular material alone. Column diameter, length, spacing, arrangement, area replacement ratio, backfill properties, and confinement supplied by the surrounding clay collectively control stress concentration and deformation within the reinforced zone (**Black et al., 2011; Al-Saoudi et al., 2013; Killeen and McCabe, 2014; Mohammed, 2015; Jayarajan and Karpurapu, 2021; Dutta et al., 2025**).

For conventional unbonded granular columns, reducing the column spacing generally increases the area replacement ratio and decreases the proportion of weak clay participating directly in the loaded zone. Therefore, higher-density columns generally exhibit greater stiffness and resistance in their composite form (**Black et al., 2011; Al-Kazzaz and Al-Obaydi, 2021**). The influence of column arrangement on the strength of the composite structure cannot be evaluated separately from the effect of the surface load transfer layer. A cushion of grains will redistribute footing stresses, improve contact between the footing and the group of columns, and alter the distribution of stress between the columns and the surrounding clay (**Hegde and Sitharam, 2013; Debnath and Dey, 2017; Mehrannia et al., 2018; Abdelrahman et al., 2026**). The actual footing performance for a standard system depends on interactions of column geometry, clay confinement, and stress redistribution due to a cushion of grains. Measured footing performance results from interacting effects of column geometry, clay confinement, and cushion-mediated stress redistribution rather than from column spacing alone.

Modification of the column infill with a biopolymer introduces an additional mechanism that differs fundamentally from increasing the quantity of granular replacement. Xanthan gum (XG) was selected for the present study because it can be introduced in powder form, hydrates to form a viscous polymer network, and can develop particle bonding and pore-bridging effects without relying on cementitious reactions. It also has comparatively established geotechnical literature in both granular and fine-grained soils (**Jang and Jia, 2020; Moghal and Vydehi, 2021**). Nevertheless, XG is not assumed to be universally superior to other biopolymers. Its engineering response is strongly dependent on soil composition, polymer dosage, water availability, preparation route, and hydration or drying history (**Chang et al., 2015; Chen et al., 2019; Ni et al., 2021**). These dependencies are particularly important for the present column system because introducing a binder changes the material response from predominantly frictional granular behavior toward a combined frictional–bonded response.

This also implies that an increase in the XG dosage will not necessarily lead to a corresponding increase in column resistance. Low dosages could lead to limited modification of the granular skeleton by discontinuous polymer coverage or weak bonding. Particle bridging and improved apparent stiffness with increasing dosage may occur at sufficient water availability. Beyond this point, more severe effects such as agglomeration, uneven polymer distribution, hydration gradients, or uneven grain-to-grain contact may occur. Therefore, the XG-treated soil exhibits non-monotonic (and often dose-dependent) properties (**Ni et al., 2021; Askari et al., 2025**). In addition, this behavior becomes even more complicated under different moisture conditions, where hydration results in favorable gel formation and interaction between particles, while subsequent drying leads to a consolidation of developed bonds, but possibly non-uniform moisture and stiffness profiles (**Chang et al., 2015; Chen et al., 2019**). XG treatment affects soil properties, and this is related to dosage and moisture condition.



The preparation method employed in the present study is another difference from most of the literature on XG-treated-soils. The previous studies have mainly focused on the material specimens treated with XG or bulk soil mixtures under specific mixing, water addition, immersion, hydration, or drying conditions (**Chang et al., 2015; Chen et al., 2019; Ni et al., 2021; Askari et al., 2025**). These studies show that the soil is sensitive to the dosage and moisture history of XG, but they do not directly show how these material-scale mechanisms control a set of individual XG-treated sand columns placed in soft clay under a shallow footing. In the current setup, the XG powder is dry-blended with the sand prior to column installation, and no extra water is added directly to the XG-sand mixture. The moisture redistribution from the surrounding clay during the conditioning period is therefore important for the development of polymer bonding. At the same time, each column is isolated by the clay, mechanically coupled to adjacent columns, and loaded by the overlying sand cushion. The footing response is therefore a result of coupled material, hydraulic, interface and group-interaction mechanisms, and not the strength of an isolated XG-treated sand specimen.

This coupling is an important conflict between the mechanisms expected from conventional granular columns and those introduced by XG treatment. In the case of untreated columns, it is generally desirable to have closer spacing as the nominal area replacement ratio increases and the volume of weak clay between the adjacent columns decreases. Addition of XG can reinforce, weaken, or even reverse this geometric advantage if changes in polymer distribution, hydration, interparticle bonding, column stiffness, or column-clay compatibility affect load transfer in the reinforced zone. Increasing the XG dosage will improve the performance of the treated infill only if the additional polymer is able to contribute to the bonding process through adequate and reasonably uniform hydration. Column spacing and XG dosage are not independent improvement variables.

The critical research gap is therefore not simply the absence of additional XG-treated soil tests, but the absence of controlled experimental evidence describing how column-group geometry interacts with dry-blended XG dosage when the treated sand is confined as discrete columns within soft clay and loaded through a shallow footing. Conventional granular-column research establishes the importance of spacing, area replacement ratio, confinement, and group interaction (**Hughes and Withers, 1974; Andreou et al., 2008; Black et al., 2011; Killeen and McCabe, 2014**), whereas the XG literature establishes the importance of dosage, hydration, preparation route, and moisture history (**Chang et al., 2015; Chen et al., 2019; Ni et al., 2021; Askari et al., 2025**). What remains unresolved is whether the conventional benefit of a denser column arrangement persists when the granular infill is modified by a hydration-dependent binder, and whether an XG dosage that is favorable at one spacing remains favorable when the group geometry changes.

Accordingly, the present study evaluates the coupled influence of column spacing and dry XG dosage on the pressure-settlement response of a square footing resting on soft clay improved with a 50 mm sand cushion and a 4×4 group of sand columns. The column number, diameter, length, cushion thickness, footing dimensions, clay preparation condition, loading rate, and conditioning interval were maintained constant, while the clear column spacing was varied between 20 and 35 mm and the XG dosage between 0%, 0.5%, 1%, and 2% by dry sand mass. These two spacings correspond to normalized center-to-center spacing ratios, (S_c/d), of 1.80 and 2.40. Untreated clay and cushion-only models were included as reference conditions so that the contribution of surface load spreading could be distinguished from the additional response associated with the column groups. The study



specifically examines whether spacing and XG dosage interact in controlling the pressure–settlement response rather than attempting to derive a universal optimum dosage or design spacing. The comparison is made on the basis of the complete pressure–settlement response, pressure at ($s/B = 11\%$), bearing capacity ratio, and spacing–dosage treatment contrasts. The conditioning period was short, column hydration and post-installation geometry were not directly measured, and finite rigid boundaries were used, so the trends and optimum configuration are considered to be model-scale experimental results and not generalized field-design values.

2. MATERIALS AND METHOD

2.1 Experimental Program

The experimental program was designed to isolate the coupled effects of column-group spacing and XG dosage while keeping the other principal model parameters constant. A 60×60 mm square footing was supported on soft clay improved with a 50 mm sand cushion and a 4×4 group of sixteen sand columns. The nominal diameter, d , of each column was 25 mm and the nominal length, L , was 150 mm. The fixed geometry was then $d/B = 0.417$, $L/d = 6.0$, and cushion thickness/ $B = 0.833$. These dimensions are for the geometry of the present laboratory model and are not meant to be unique or optimum for a field-scale configuration. Both absolute and normalized spacing parameters were retained because the mechanical significance of column spacing depends on its magnitude relative to the column diameter. For the 25 mm nominal diameter, clear spacings of 20 and 35 mm correspond to $g/d = 0.80$ and 1.40, while the corresponding center-to-center ratios are $Sc/d = 1.80$ and 2.40. Reporting Sc/d permits the local spacing geometry to be interpreted independently of the absolute laboratory dimensions and facilitates comparison with other granular-column configurations (**Black et al., 2011; Al-Kazzaz and Al-Obaydi, 2021**). However, these normalized ratios characterize local inter-column geometry only. Because the present tests used a finite 4×4 group with a constant number of columns, changing Sc/d also changed the total group footprint and finite-group replacement ratio. Normally spacing should therefore not be interpreted as the only geometric variable governing the measured footing response. The 20 mm spacing thus represents the denser interaction case where there is only $0.80d$ of clear clay separating adjacent nominal column surfaces, whereas the 35 mm spacing represents the more open interaction case with $1.40d$ of clear clay separating adjacent columns. The denser spacing gives a higher nominal replacement ratio and closer spacing between adjacent column influence zones, thus favoring stronger interaction between neighboring columns and the surrounding composite ground. The more open spacing increases the separation between adjacent columns influence zones and decreases the nominal replacement ratio due to the larger clay ligament between adjacent columns. The objective for using these two spacings was not to recommend specific 20 or 35 mm spacings but instead to set up a controlled difference in group interaction. When comparing the results, it is important to keep in mind that changing the spacing not only changes inter-column separation, local group geometry, replacement ratio, and overall group footprint. but also changes the overall group footprint because the number of columns is kept constant at sixteen.

The nominal column length was fixed at 150 mm ($L/d = 6.0$) such that the relative slenderness of the columns was held constant between spacing and dosage comparisons. Maintaining the relative column slenderness allowed the sand columns to interact with the

clay under the same relative embedded length without introducing column length as an independent variable. The thickness of the overlying sand cushion was kept constant at 50 mm in all the column-supported models to ensure that the load transfer through the surface granular layer was similar for all the column-supported models. Thus, maintaining the cushion thickness also eliminated the effect of cushion thickness as an additional design factor.

Each spacing was tested with XG dosages of 0%, 0.5%, 1%, and 2% by dry sand mass. The column number, nominal diameter, nominal length, footing dimensions, cushion thickness, target clay condition, loading rate, and conditioning duration were maintained constantly. References consisted of untreated clay (UC) and clay with the 50 mm sand cushion only (SC). All models containing XG were kept under covered conditions for three days prior to testing. This time period was only employed as a standard short-term conditioning period and is not regarded as a complete or uniform hydration period as described in Section 2.6. The diffusion-based screening and the lack of direct column and clay moisture-profile measurements are therefore explicitly considered as experimental limitations, and not as a reason to assume equilibrium hydration.

2.2 Materials

2.2.1 Clay Soil

The foundation soil was classified as low-plasticity clay (CL) according to the Unified Soil Classification System. Particle-size analysis indicated approximately 53% clay-sized particles ($<2\ \mu\text{m}$), 44% silt, and 3% sand. The measured organic content was below 0.01%, while the total dissolved solids (TDS) content was 2.21% and the pH was 7.2. The principal physical and index properties are summarized in **Table 1**, and the particle-size distribution is shown in **Fig. 1**.

Table 1. Physical and index properties of the clay soil used in the model tests.

Property	Value	Standard
Specific gravity, G_s	2.69	(ASTM D854, 2014)
Liquid limit, LL (%)	38	(ASTM D4318, 2017)
Plastic limit, PL (%)	17	(ASTM D4318, 2017)
Plasticity index, PI (%)	21	Calculated
Sand (%)	3	(ASTM D422, 2007)
Silt (%)	44	(ASTM D422, 2007)
Clay (%)	53	(ASTM D422, 2007)
USCS classification	CL	Based on test results
Organic matter (%)	< 0.01	(ASTM D2974, 2014)
Total dissolved salts, TDS (%)	2.21	(ASTM D5907, 2018)
pH	7.2	(ASTM D4972, 2019)
Water content in preparation (%)	25	Adopted test condition
Target Undrained shear strength, c_u (kPa)	≈ 17	Vane shear test

For preparation of the model beds, a water content of approximately 25% and an undrained shear strength, c_u , of approximately 17 kPa were adopted as the target clay condition. Vane shear testing was used as a pre-loading preparation check rather than as a replicated characterization program for every model. Accordingly, the value of 17 kPa reported in **Table 1** represents the nominal target condition used to prepare the soft-clay beds and

should not be interpreted as a statistically established mean strength common to all individual tests. The limitations of the retained vane-shear records and the resulting uncertainty in between-model strength consistency are discussed in Section 2.4.

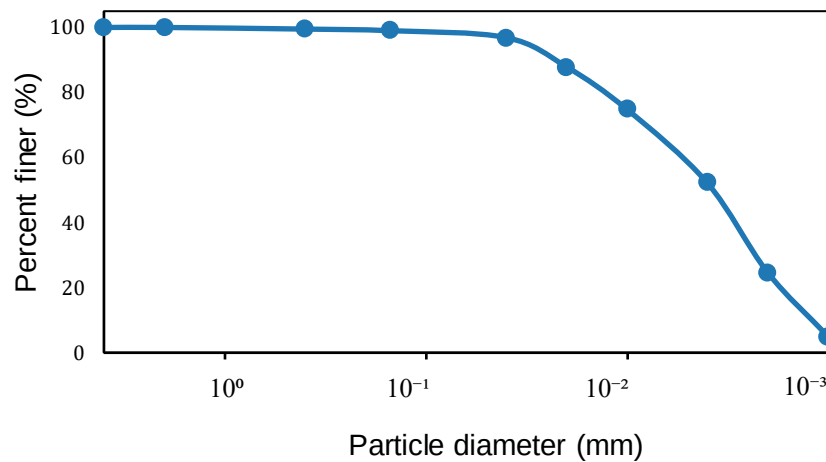


Figure 1. Particle-size distribution curve of the clay soil.

2.2.2 Sand

To avoid differences in the granular materials used for the two functions, the same sand was used for the surface cushion and the column infill. Sieve analysis showed that 95.8% passed sieve No. 4, 70.6% passed No. 30, 34.6% passed No. 50, 10% passed No. 100, and 5% passed No. 200, with a sulphate (SO_3) content of 0.28%. The grain-size sand distribution is plotted in **Fig. 2**.

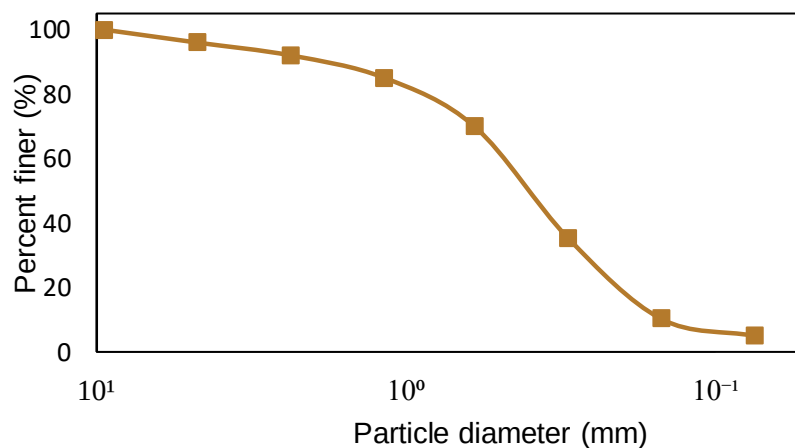


Figure 2. Particle-size distribution curve of the sand used for the cushion and sand columns.

2.2.3 Xanthan Gum

Xanthan gum (XG) was selected for the present experimental program because its powder form is compatible with the adopted dry-batching procedure and because hydration can subsequently develop viscous polymer networks and particle-bridging effects within the granular infill. The selection was method-specific and does not suggest that XG is universally

superior to guar gum, agar, or other biopolymers, whose behavior also depends on polymer chemistry, soil composition, water availability, concentration, and preparation method. (Jang and Jia, 2020; Moghal and Vydehi, 2021).

The four different amounts of XG added were 0%, 0.5%, 1%, and 2% by dry sand mass. The 0% value represents the case without adding XG and is necessary to distinguish between the effect of adding XG and the contribution of the sand columns. The three remaining values are chosen to represent low, medium, and higher contents of XG within a range previously explored in geotechnical applications. Previous studies on XG-treated soils show that the treatment efficiency depends on the dosage and that the highest content does not always produce the best results (Chang et al., 2015; Ni et al., 2021; Askari et al., 2025). For example, (Chang et al., 2015) concluded that the soils investigated in their study were effectively strengthened by around 1-1.5%. (Askari et al., 2025) studied the effects of XG dosages of 0.5%, 1%, and 2% for silty sand. Therefore, the current 0.5-2% range of XG dosages is chosen to cover a wide enough range to establish whether the treatment reveals a gradual increase or has an optimal content. The percentages are not recommended for use in field design, and the optimum found in this column test system should not be directly applied to other soils, preparation methods, or hydration conditions.

The amounts of XG needed for each treated model are reported in terms of the dry sand mass that was used to fill the columns. The XG powder was batched by mass, mixed with the dry sand, and thoroughly mixed until no streaks or distinct clumps of XG were present. All treated models followed the same batching criteria and preparation protocol. XG was not added to the surrounding clay or the surface cushion. It was only added to the column sand. The adopted procedure controlled the nominal mass ratio and macroscopic visual homogeneity, but it did not verify microscale polymer distribution. No samples were taken from different parts of the dry mixture for polymer-content measurement, and no chemical mapping, microscopy, tracer test, or other quantitative mixing-uniformity assessment were performed. Accordingly, the statement that no visible segregation or agglomeration remained should not be interpreted as proof of uniform XG concentration throughout each column. Local differences in dry-powder distribution may therefore have persisted and, together with the unverified hydration distribution described in Section 2.6, represent potential sources of variability in the XG-treated responses. The XG powder used in the experimental program is shown in Fig. 3.



Figure 3. Xanthan gum powder is used as a dry additive in the sand-column infill.



2.3 Model Setup and Testing Equipment

Tests were performed in a steel box with a rigid wall of dimensions: $700 \times 700 \times 800$ mm inside. A 60×60 mm square steel footing was placed in the center of the surface. Displacement was imposed through the hydraulic loading system at a constant rate of 1 mm/min. This rate was selected with reference to the constant-rate penetration range of 0.25–1.25 mm/min specified for cohesive soils in (**ASTM D1143/D1143M, 2020**), although that standard applies to axial testing of deep foundation elements and is used here only as a loading-rate reference rather than as a governing shallow-footing test standard.

The footing was centered within the 700×700 mm plan area of the rigid steel box. The distance from the footing center to each side wall was therefore 350 mm, giving a clear footing-edge-to-wall distance of 320 mm, equivalent to $5.33B$, where $B = 60$ mm. The internal box depth of 800 mm corresponded to $13.33B$. The nominal overall widths of the 4×4 column groups were 160 mm for $g = 20$ mm and 205 mm for $g = 35$ mm. Consequently, the minimum clear distances from the outside edge of the column group to the side wall were 270 mm and 247.5 mm, corresponding to $4.50B$ and $4.13B$, respectively.

These normalized clearances position the footing and full columns a few footing widths away from the sidewalls in order to minimize the impact of the primary load region on the box walls. However, due to the presence of rigid steel sidewalls in the test container, it is not possible to show that there was no effect of the boundaries. In laboratory model tests, rigid lateral boundaries can restrict outward deformation of the soil and thereby modify stress spreading and confinement relative to an effectively unbounded soil mass. This consideration is particularly relevant to sand columns because their response depends on lateral confinement from the surrounding clay (**Black et al., 2011; Killeen and McCabe, 2014**).

The same box and footing position were used for every test, which maintained a common boundary condition throughout the experimental program. However, changing the column spacing also changed the overall group footprint; therefore, the outer columns of the $g = 35$ mm array were closer to the walls than those of the $g = 20$ mm array. No companion tests were performed using a larger container or alternative boundary clearances. Accordingly, any residual influence of the rigid walls on lateral clay deformation, stress redistribution, or column confinement cannot be quantified or completely separated from the measured spacing effect. The resulting comparisons are therefore interpreted as model-scale responses under the reported finite-boundary conditions rather than as boundary-independent field responses. The testing arrangement and principal dimensions are shown in **Figs. 4 and 5** and summarized in **Table 2**.

2.4 Preparation of Model Beds

The clay used for each model was prepared using the same material source and a common preparation procedure. Water content was adjusted before placing the clay towards the desired value of about 25%. Clay was then placed in layers, hand-compacted in the same way and leveled to create the model bed. Controlling the material source, water content, placement sequence and hand-compaction procedure was intended to minimize preparation differences between the model tests.

Water content and vane-shear tests were conducted before loading to determine if the prepared clay was suitable for the soft-clay condition. The target preparation condition was an undrained shear strength of $c_u \sim 17$ kPa. The retained experimental records, however,

do not include a complete set of individual vane-shear readings for each model, replicate measurements within each bed, or a pre-defined numerical acceptance band around 17 kPa. Therefore, a model-by-model c_u dataset cannot be reconstructed and the mean, standard deviation, coefficient of variation, or statistical equivalence of clay strength between the various tests cannot be reported. The value $c_u \approx 17$ kPa should therefore be understood as the nominal strength condition aimed for in the preparation of the models, not as an indication that all clay beds had the same undrained shear strength. Procedural control was achieved by using the same source of clay, target water content, placement procedure, hand-compaction method, and pre-loading vane check, but some between-model variation in clay consistency cannot be ruled out. Any uncertainty in the value of c_u is a source of experimental uncertainty because both footing response and column confinement depend on the surrounding clay strength.

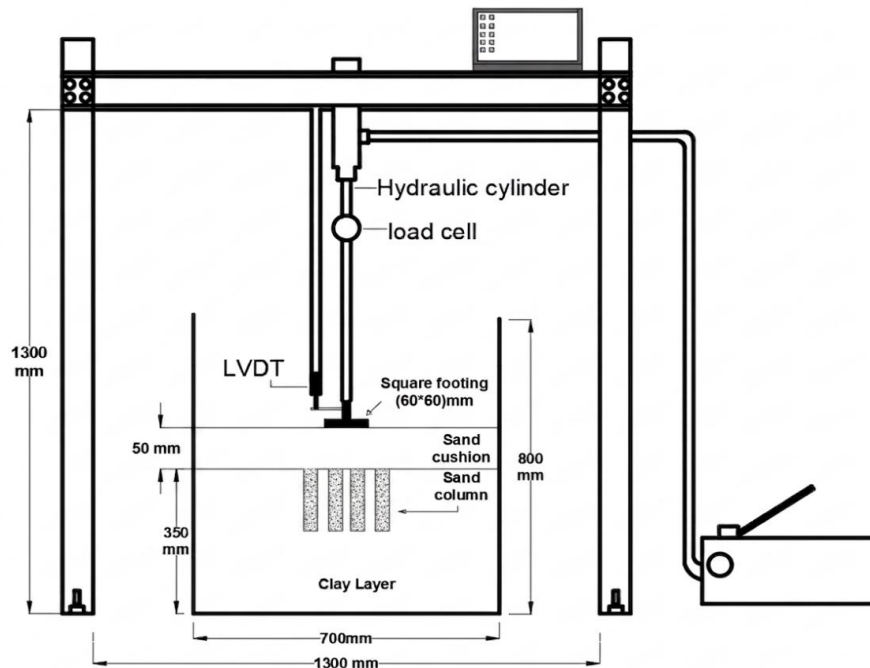


Figure 4. Schematic layout of the model testing setup.



Figure 5. Laboratory arrangement used for static loading of untreated and improved clay models.



The untreated-clay model (UC), the sand-cushion reference model (SC), and all column-supported models were prepared using this same nominal bed-preparation procedure. Comparisons among configurations are therefore made on the basis of a common target clay condition, while the absence of retained replicate cu measurements is explicitly considered when interpreting relatively small differences between individual tests.

Table 2. Model geometry and testing equipment used in the experimental program.

Item	Description / Value
Model box dimensions	700 × 700 × 800 mm
Footing shape and size	Square, 60 × 60 mm
Load-measuring device	5-tonne S-shaped load cell
Settlement-measuring device	Two LVDTs (averaged)
Data acquisition	PC-based system with LabView
Column type and number	Sand columns; 16 in 4 × 4 group
Column diameter and height	25 mm; 150 mm
Column spacing (Case 1 / Case 2)	20 / 35 mm clear spacing; $S_c = 45 / 60$ mm
Sand cushion thickness	50 mm
Xanthan gum contents tested	0%, 0.5%, 1%, and 2% by dry sand mass
XG conditioning interval	3 days under covered conditions; complete or uniform hydration was not verified
Footing-edge-to-wall clearance	320 mm = 5.33B
Box depth	800 mm = 13.33B
Nominal group width, $g = 20$ mm	160 mm = 2.67B
Nominal group width, $g = 35$ mm	205 mm = 3.42B
Group-edge-to-wall clearance, $g = 20$ mm	270 mm = 4.50B
Group-edge-to-wall clearance, $g = 35$ mm	247.5 mm = 4.13B
Loading mode and rate	Displacement controlled, 1 mm/min
Time to $s/B = 11\%$	Approximately 6.6 min
Drainage condition	Short-duration loading intended to limit drainage; undrained condition not verified

2.5 Preparation of Sixteen-Column Models

The sixteen column locations were symmetrically marked in a 4 × 4 array. At each location, a steel sleeve with an internal diameter of 25 mm was inserted to a depth of 150 mm. Untreated sand or XG-sand was then placed into the sleeve in successive lifts and compacted manually while the sleeve provided temporary lateral confinement. After filling, the sleeve was withdrawn gradually and approximately axially while the infill was retained in place, with the intention of limiting drag on the column material and disturbance of the surrounding clay.

The installed column geometry was not instrumentally verified during or after sleeve extraction. In particular, no measurements were made of radial deformation, post-extraction column diameter, local necking or enlargement, extraction-induced suction, or the spatial extent of disturbance in the adjacent clay. Consequently, the reported diameter of 25 mm represents the nominal forming diameter defined by the sleeve rather than a measured post-installation column diameter. The calculated (S_c/d) ratios and nominal area replacement ratios therefore also refer to the intended geometry and should not be interpreted as measurements of the final in-soil column cross-sections.

This limitation is physically relevant because the withdrawal of the sleeve can locally change the cross-section of the column or affect the column–clay interface by drag suction or remolding of the surrounding soft clay. Such effects could modify lateral confinement, interface stress transfer, and the effective amount of granular material participating in the reinforced zone. The measured footing response is not distinguishable from the effects of spacing and XG dosage due to the lack of measurement of these quantities, and therefore, the effects of geometric and interface variability cannot be separated from the effects of spacing and XG dosage. The same installation sequence was, however, used for all column models to ensure procedural consistency, and the comparisons made are therefore interpreted as responses of columns prepared by a common nominal installation method, not as tests of geometrically verified columns.

The 4×4 configuration was chosen not as an assumed optimum or field-design configuration, but as a controlled finite-group configuration. The fourfold geometric symmetry about the center of the square footing was provided by an even square array, and the same sixteen-column configuration was maintained with varying spacing and XG dosage. More important, sixteen columns were used to give relatively internal and peripheral positions within the treated zone, so that the footing–cushion system could be applied to a real column group instead of a single column or a very small group of columns. This is important because the response of small granular-column groups is dependent on inter-column and footing interaction, and peripheral columns may respond differently than more confined internal columns (**Black et al., 2011; Killeen and McCabe, 2014**). The 4 × 4 layout was not chosen to simulate an infinite column grid or to determine an optimum number of columns, but rather to provide a common experimental platform for comparing the two spacing–dosage series. The effect of the number of columns alone cannot be distinguished from the reported response as only one group size was tested. The nominal geometry is presented in **Fig. 6** and the installed group prior to the sand cushion 50 mm is presented in **Fig. 7**.

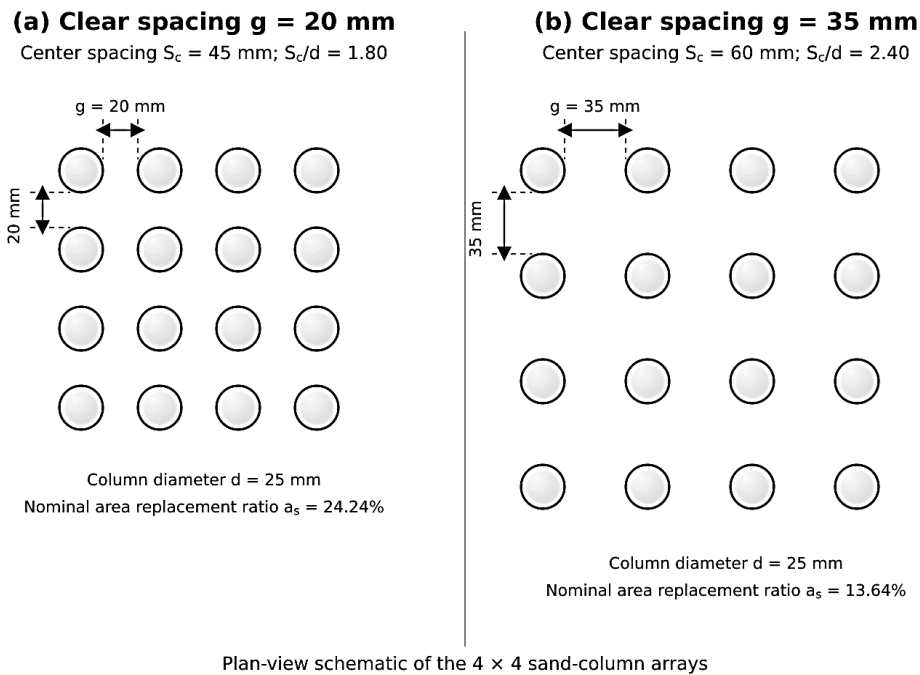


Figure 6. Plan view of the 4 × 4 arrays. The reported 20 and 35 mm values are clear edge-to-edge spacings; $S_c/d = 1.80$ and 2.40, respectively.



Figure 7. Layout of the 4×4 sand columns embedded in the clay bed prior to placement of the 50 mm sand cushion.

2.6 Preparation of Xanthan-Modified Columns

XG was dry-mixed with the sand before column installation, and the same installation procedure was applied to all untreated and XG-modified column models. After preparation, the XG-containing models were maintained under covered conditions for three days before loading. This interval was adopted as a standardized short-term conditioning period so that all treated models were tested after the same elapsed time while uncontrolled surface evaporation was limited. The three-day interval is not considered evidence of complete curing or uniform XG hydration because the development of XG bonding is strongly dependent on moisture availability and hydration–drying history (**Chang et al., 2015; Chen et al., 2019**).

Because water was not added directly to the XG–sand infill, the moisture required for XG hydration had to originate from the surrounding clay. The maximum nominal radial transport distance from the column–clay interface to the center of the 25 mm diameter column was 12.5 mm. For diffusion-controlled transport, the characteristic diffusion time varies with the square of the transport distance divided by the diffusion coefficient (**Dentz et al., 2023**). This relationship was used here only as an order-of-magnitude screening tool to determine the effective diffusivity that would correspond to a characteristic transport distance equal to the nominal column radius during the three-day conditioning interval.

The screening calculation is expressed as:

$$De_{req} = \frac{R^2}{tc} \quad (1)$$

where De_{req} is the characteristic effective diffusivity required for a transport distance of the order of the nominal column radius during the conditioning interval, R is the nominal radial transport distance (0.0125 m), and tc is the conditioning time (259,200 s).

By applying the values in the equation, this leads to $\frac{(0.0125)^2}{259200} = 6.03 \times 10^{-10} \text{ m}^2/\text{s}$

Eq. (1) indicates that an effective diffusivity of the order of $6.03 \times 10^{-10} \text{ m}^2/\text{s}$ would be required for the characteristic diffusion length to become comparable with the nominal column radius within three days. The value is not a measured diffusivity of the clay-column system and does not show that moisture was actually delivered to the center of the column.

It just provides a transport scale threshold as per the diffusion relationship reported by **(Dentz et al., 2023)**. Other factors such as the hydraulic characteristics of the clay, suction, the column-clay interface, pore structure of the sand column, and changes occurring in the XG-sand mixture during hydration can also impact the actual moisture transfer process.

The clay-column system did not yield any effective moisture diffusivity, hydraulic conductivity or suction measurements. Furthermore, no water content measurements were made at the perimeter or center of the column after conditioning, and no radial moisture-loss profile was measured in the surrounding clay. Thus, from the present experiments it is not possible to determine whether three days was enough time for moisture to reach and adequately hydrate the entire 25 mm column. The three days should therefore be taken as a period of equal conditioning and not as a proven hydration period. A significant experimental limitation and potential source of variation in the XG-treated responses is incomplete or spatially non-uniform hydration. Replicated testing should be conducted in the future to directly measure water-content profiles in the column and adjacent clay, suction, and moisture-transport properties to confirm the extent and uniformity of hydration. The test matrix and the normalized spacing, two complementary measures of replacement ratio, and the available compaction information are summarized in **Table 3**. The conventional square unit-cell ratio, as_{cell} , is preserved as representing the local geometric effect of center-to-center spacing and is often used when interpreting regular granular-column arrays **(Black et al., 2011; Killeen and McCabe, 2014)**. A second quantity, as_{group} , is also reported, which is the total nominal column area divided by the square plan area enclosed by the outer edges of the group, as in the present experiments. This distinction prevents the unit-cell ratio from being misinterpreted as the actual finite-group footprint replacement ratio.

Table 3. Test matrix, normalized geometry, area replacement ratios, and compaction-density reporting.

Model code	Description	Array	g (mm)	Sc/d	XG (%)	as_{cell} (%)	Wg (mm)	as_{group} (%)	Dry unit weight, γ_d (kN/m ³)
UC	Untreated clay bed	—	—	—	—	—	—	—	—
SC	Clay + 50 mm cushion	—	—	—	—	—	—	—	—
16SC-S20-0XG	Cushion + untreated columns	4 × 4	20	1.80	0	24.24	160	30.68	NR
16SC-S20-0.5XG	Cushion + 0.5% XG columns	4 × 4	20	1.80	0.5	24.24	160	30.68	NR
16SC-S20-1XG	Cushion + 1% XG columns	4 × 4	20	1.80	1	24.24	160	30.68	NR
16SC-S20-2XG	Cushion + 2% XG columns	4 × 4	20	1.80	2	24.24	160	30.68	NR
16SC-S35-0XG	Cushion + untreated columns	4 × 4	35	2.40	0	13.64	205	18.69	NR



16SC-S35-0.5XG	Cushion + 0.5% XG columns	4 × 4	35	2.40	0.5	13.64	205	18.69	NR
16SC-S35-1XG	Cushion + 1% XG columns	4 × 4	35	2.40	1	13.64	205	18.69	NR
16SC-S35-2XG	Cushion + 2% XG columns	4 × 4	35	2.40	2	13.64	205	18.69	NR

Note: $Sc = d + g$, where $d = 25$ mm. The unit-cell replacement ratio was calculated as $as_{cell} = 100 * \pi * \frac{d^2}{(4 * Sc^2)}$, giving 24.24% and 13.64% for $g = 20$ and 35 mm, respectively. For the finite 4×4 square groups, the nominal group width was calculated as $Wg = d + 3Sc$, giving $Wg = 160$ and 205 mm. The corresponding finite-group footprint replacement ratio was calculated as $as_{group} = 100 * 16 * \pi * \frac{d^2}{4 * Wg^2}$, giving 30.68% and 18.69%, respectively. Both calculations use the nominal sleeve diameter; post-installation column diameters were not measured. NR = not recorded. Neither a target nor an achieved dry unit weight was retained for the column infill; therefore, no compaction-density value has been reconstructed retrospectively.

The original experimental records did not retain either a prescribed target dry unit weight or measured achieved dry unit weight for the sand or XG-sand column infill. Column construction was controlled procedurally by using the same successive-lift placement and manual-compaction method for all models, but procedural consistency cannot demonstrate equal density. This is an important limitation because granular-column resistance is affected by backfill density, friction, and stiffness (Al-Saoudi et al., 2013; Mohammed, 2015). Therefore, possible between-model variation in column compaction cannot be separated quantitatively from the effects of spacing and XG dosage.

2.7 Loading Procedure and Data Reduction

The footing was centered on the prepared model surface and loaded under displacement control at a constant rate of 1 mm/min. The selected rate lies within the 0.25–1.25 mm/min constant-rate penetration range specified for cohesive soils in (ASTM D1143/D1143M, 2020). The ASTM procedure relates specifically to deep foundation elements; therefore, it is cited here only as a reference for the adopted displacement rate and not as evidence that the present shallow-footing model tests fully conform to (ASTM D1143/D1143M, 2020).

The principal comparison criterion used in this study was $s/B = 11\%$, corresponding to a footing settlement of 6.6 mm. At 1 mm/min, this settlement was reached approximately:

$t_{11} = \frac{6.6}{1.0} = 6.6$ min. Thus, the principal bearing comparisons were obtained during a relatively short loading interval. The selected rate was intended to restrict the time available for drainage from the low-permeability clay and thereby emphasize short-term response. However, undrained conditions were not experimentally verified. No pore-water-pressure transducers were installed, and neither excess pore-pressure generation nor dissipation was measured during loading.

The drainage condition is further complicated by the presence of the sand columns. Untreated sand columns may provide preferential drainage paths through the clay, while XG addition may alter water movement within the column infill. Hydraulic conductivity of the untreated and XG-modified columns was not measured. Consequently, identical drainage conditions cannot be assumed for all configurations, and the observed pressure-settlement response should not be interpreted as a rigorously verified undrained bearing-capacity response. The results are therefore described as short-duration model responses obtained under a common imposed loading rate, with the extent of drainage remaining an



experimental uncertainty. All measured loads were converted to pressure, according to Eq. (2):

$$q = \frac{P}{A} \quad (2)$$

where q is the applied surface pressure, P is the measured vertical load, and A is the footing area (60×60 mm). The footing settlement was expressed as a settlement ratio using Eq. (3):

$$\frac{s}{B} (\%) = \left(\frac{\text{settlement}}{\text{breadth of footing}} \right) \times 100 \quad (3)$$

where s is footing settlement and $B = 60$ mm.

The pressure–settlement curves did not exhibit a distinct peak from which a unique ultimate bearing pressure could be identified. A common settlement-based reference was therefore required for consistent comparison among the untreated, cushion-only, and column-supported models. In model stone-column testing, (Fattah et al., 2011) evaluated several failure definitions and reported a criterion in which the comparison settlement is taken as the smaller of $0.5d$ and $0.11B$. In the present geometry, $0.5d = 12.5$ mm, whereas $0.11B = 6.6$ mm. The smaller value is therefore 6.6 mm, corresponding to $s/B = 0.11$ or 11%.

The value $s/B = 11\%$ was consequently adopted as a common deformation-based comparison criterion for extracting pressure, BCR, and treatment contrasts from all tests. Its purpose is to provide an identical normalized settlement at which configurations can be compared; it is not interpreted as a universal ultimate-bearing-capacity criterion, a serviceability settlement limit, or direct evidence that physical failure occurred at that displacement. The complete pressure–settlement curves are therefore retained and discussed together with the values extracted at $s/B = 11\%$.

The bearing performance of each improved model was evaluated using the bearing capacity ratio (BCR), defined by Eq. (4) as the applied surface pressure of the improved model divided by the applied surface pressure of the untreated clay at the same settlement ratio:

$$BCR = \frac{q_{\text{improved}}}{q_{\text{untreated}}} \quad (4)$$

The relative performance of each improved configuration was presented in terms of the bearing capacity ratio (BCR), which is the ratio of the pressure carried by the improved model to that carried by the untreated clay at the same normalized settlement. The main BCR values reported in the present study are those for $s/B = 11\%$. The term BCR is used for consistency with granular-column literature, but the reported values are settlement-based comparative ratios and should not be interpreted as ratios of independently determined ultimate bearing capacities.

The percentage change relative to the untreated clay at $s/B = 11\%$ was calculated using Eq. (5):

$$\text{Change } (\%) = \left[\frac{(q_{\text{improved}} - q_{\text{untreated}})}{q_{\text{untreated}}} \right] \times 100 \quad (5)$$

2.8 Repeatability and Statistical Scope

One model test was performed for each spacing–dosage condition. The two symmetrically positioned LVDTs were averaged to reduce the influence of settlement-reading asymmetry,



but these measurements are not independent experimental replicates. Consequently, within-condition standard deviations, confidence intervals, and inferential comparisons such as ANOVA cannot be calculated from the present dataset.

The same limitation applies to verification of clay-bed consistency. Although the beds were prepared using the same clay source, target water content, placement and hand-compaction procedure, and a target c_u of approximately 17 kPa, the retained records do not include replicate vane-shear measurements or a complete model-by-model strength dataset. Therefore, between-model variability in c_u cannot be quantified statistically. Possible differences in the initial clay condition must consequently be considered together with other preparation uncertainties when interpreting the measured pressure differences.

The analysis is therefore limited to pressure–settlement responses, pressures at $s/B = 11\%$, BCR values, normalized geometry, and descriptive treatment contrasts. The observed differences are used to detect model-scale trends and are not considered statistically significant effects. Replicate model tests with documented water content and vane shear measurements for each prepared clay bed would be needed to increase confidence in the isolated effects of spacing and XG dosage.

3. RESULTS AND DISCUSSION

This section compares the pressure-settlement curves, BCR, and pressure at $s/B = 11\%$. UC is the reference. Interpretation focuses on the separate and coupled effects of the cushion, column geometry, and XG dosage.

3.1 Reference Models: Untreated Clay and Sand Cushion

UC reached 98.24 kPa at $s/B = 11\%$. Adding the 50 mm cushion increased the pressure to 110.76 kPa, a gain of 12.74%. The modest increase is consistent with stress spreading beneath the footing; the cushion does not provide deep reinforcement.

3.2 Response of the 20 mm Spacing Group

There is a comparison between the 20 mm clear-spacing group and the two references in **Fig. 8**. At $s/B = 11\%$, the untreated-column model (16SC-S20-0XG) reached 119.46 kPa, compared with 98.24 kPa for UC., which is a stiffer composite zone. The 0.5% XG model reached only 95.995 kPa. This result indicates that reduction of the binder content could have resulted in less contact with the direct sand and insufficient—or insufficiently uniform—bonds, which was a mechanistic explanation for the result, and was not independent of mixing or hydration variation in the current single tests.

The pressure at 1% XG was 117.326 kPa, which was a little lower than that of the untreated column. The 2% model was the strongest in the 20 mm group, with a pressure of 129.088 kPa. The endpoint order was 2% XG > 0% XG > 1% XG > 0.5% XG. Non-monotonic response indicates that the response is not always related to dosage.

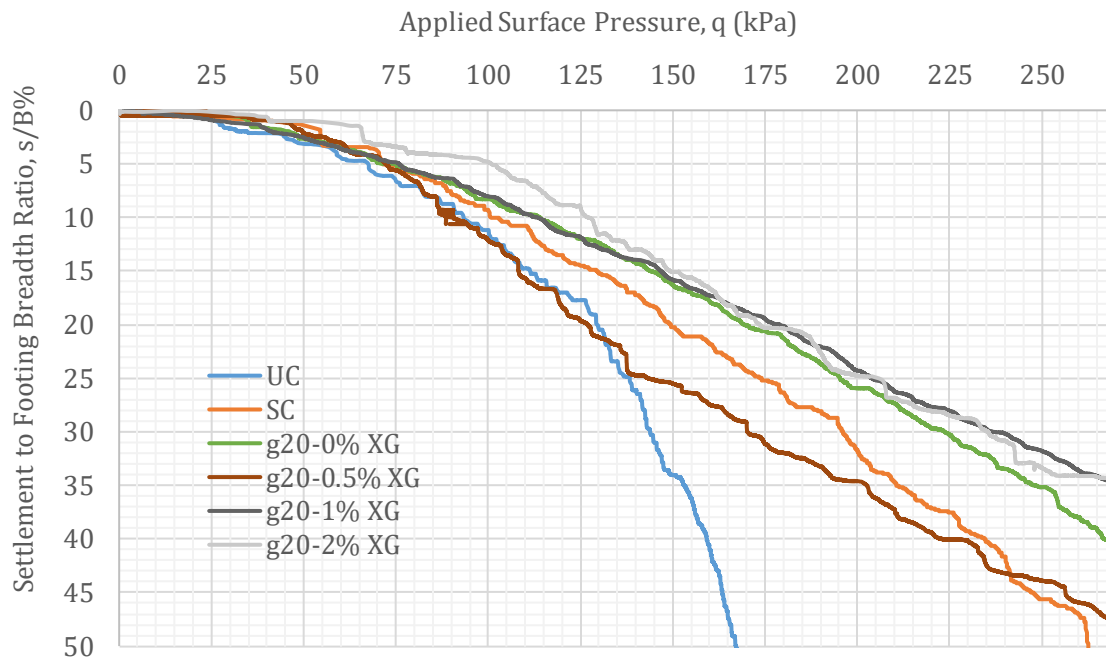


Figure 8. Applied surface pressure versus settlement ratio for the $g = 20$ mm models and reference cases. Distinct line and marker styles are used for monochrome readability.

3.3 Response of the 35 mm Spacing Group

The 35 mm clear-spacing group is given on **Fig. 9**. The untreated-column model was able to reach 99.92 kPa, which was 1.71% away from UC. The treated columns did not offer much extra resistance at the lower nominal replacement ratio. The pressure for 0.5% XG reached 126.77 kPa, despite the lower nominal replacement ratio and more open spacing. The highest pressure for the program was 174.15 kPa in 16SC-S35-1XG.

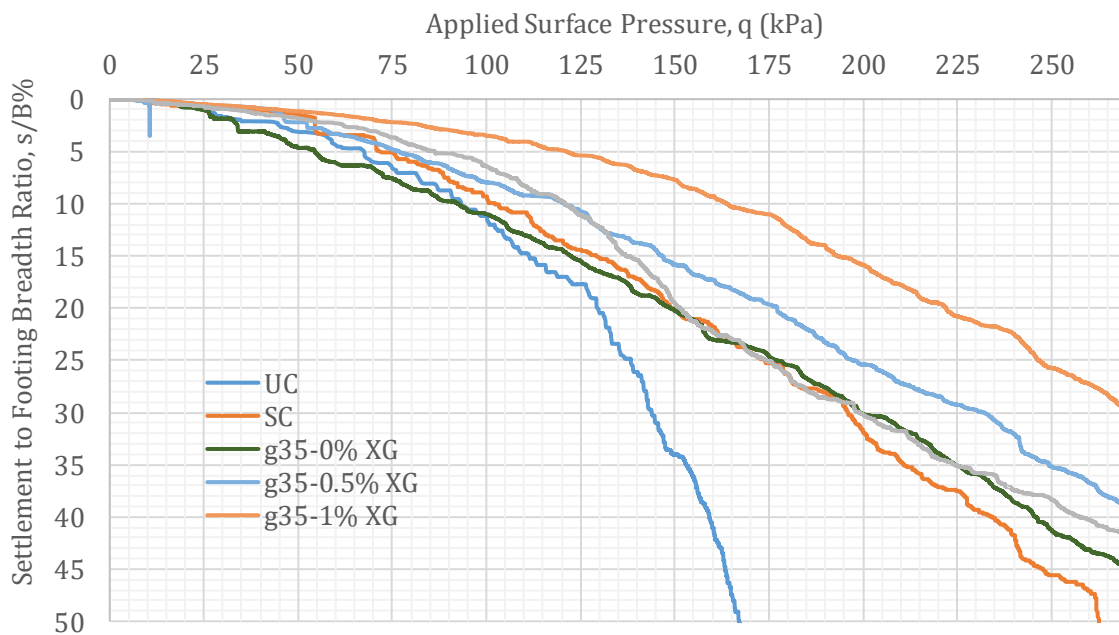


Figure 9. Applied surface pressure versus settlement ratio for the $g = 35$ mm models and reference cases. Distinct line and marker styles are used for monochrome readability.

With the increase of XG to 2% the pressure drops to 124.35 kPa. The causes are likely to be agglomeration, non-uniform hydration, change of contact between sand and the other aggregate, and/or local stiffness incompatibility, which were not measured separately. The endpoint order was 1% XG > 0.5% XG > 2% XG > 0% XG.

3.4 Influence of Column Spacing

The influence of spacing depended strongly on XG dosage. For the untreated columns, reducing the clear spacing from 35 to 20 mm increased the pressure at $s/B = 11\%$ from 99.92 to 119.46 kPa. This response is consistent with conventional granular-column behavior because the denser 20 mm arrangement contains less intervening clay and has a higher nominal area replacement ratio. The normalized geometry also changes from $Sc/d = 2.40$ and $g/d = 1.40$ for the 35 mm array to $Sc/d = 1.80$ and $g/d = 0.80$ for the 20 mm array. Accordingly, the untreated response is consistent with stronger composite interaction as neighboring columns are brought closer together (Black et al., 2011; Al-Kazzaz and Al-Obaydi, 2021).

This conventional trend did not persist after XG addition. At 0.5% XG, the 35 mm array exceeded the 20 mm array by 30.775 kPa, while at 1% XG the difference increased to 56.824 kPa, equivalent to 48.4% relative to the 20 mm value. At 2% XG, the difference decreased to -4.738 kPa, with the 20 mm array producing a slightly higher response. Therefore, reducing spacing did not consistently improve the XG-modified column system.

These results indicate that the spacing effect cannot be interpreted solely through nominal replacement ratio or overlap of neighboring column influence zones once XG is introduced. Binder development, hydration, modified column stiffness, and column–clay interaction may alter the conventional geometric response. These mechanisms were not measured independently and are therefore proposed only as possible explanations. Furthermore, because the same sixteen columns were retained, changing spacing also altered the total group footprint. The reported contrasts consequently represent the response of the two tested array geometries rather than a pure spacing effect at constant treatment footprint.

3.5 Bearing Capacity Ratio

BCR is plotted against the range of settlements measured as shown on Fig. 10. At $s/B = 11\%$, the highest BCR was 1.773 for 16SC-S35-1XG, and the lowest was 0.977 for 16SC-S20-0.5XG. The full curves and the endpoints all indicate that 2% XG was best at 20 mm spacing, and 1% was best at 35 mm spacing.

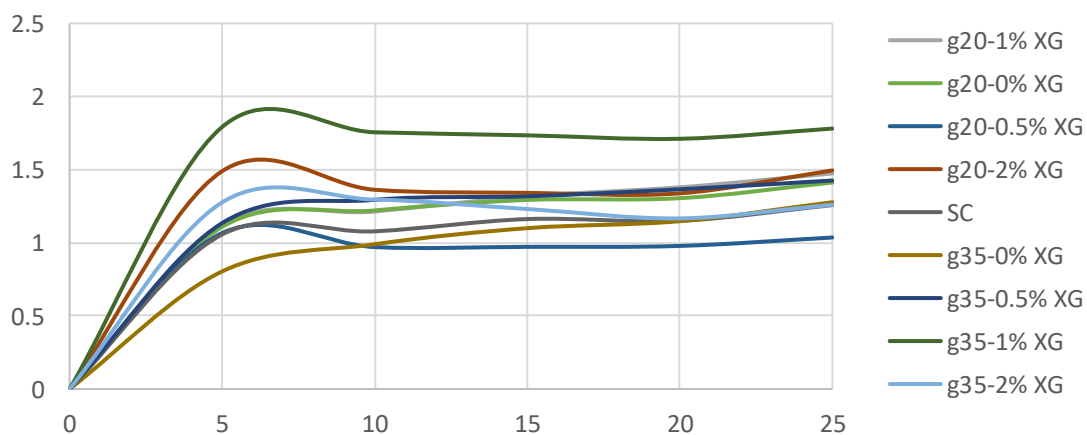


Figure 10. Variation of BCR with settlement ratio.

3.6 Summary at the Common Comparison Settlement ($s/B = 11\%$)

Table 4 and **Figs. 11 and 12** summarize the measured response at the common comparison settlement of $s/B = 11\%$. This settlement was selected as described in Section 2.7 to provide a consistent normalized deformation level across all configurations rather than to define a universal ultimate bearing capacity. At this point, the sand cushion increased the applied pressure by 12.74% relative to untreated clay. The best-performing 20 mm configuration was 16SC-S20-2XG, with 129.088 kPa and BCR = 1.314, whereas the highest response in the complete test series occurred for 16SC-S35-1XG, with 174.15 kPa and BCR = 1.773. These values are therefore interpreted as comparative pressures and BCR values at the specified deformation level.

Table 4. Applied surface pressure, settlement-based BCR, and percentage change relative to untreated clay at the common comparison settlement of $s/B = 11\%$.

Model	Pressure at $s/B = 11\%$ (kPa)	BCR	Change vs. UC (%)
Untreated clay (UC)	98.24	1.000	0.00
Sand cushion (SC)	110.76	1.127	+12.74
16SC-S20-0XG	119.46	1.216	+21.60
16SC-S20-0.5XG	95.995	0.977	-2.29
16SC-S20-1XG	117.326	1.194	+19.42
16SC-S20-2XG	129.088	1.314	+31.40
16SC-S35-0XG	99.92	1.017	+1.71
16SC-S35-0.5XG	126.77	1.290	+29.04
16SC-S35-1XG	174.15	1.773	+77.27
16SC-S35-2XG	124.35	1.266	+26.58

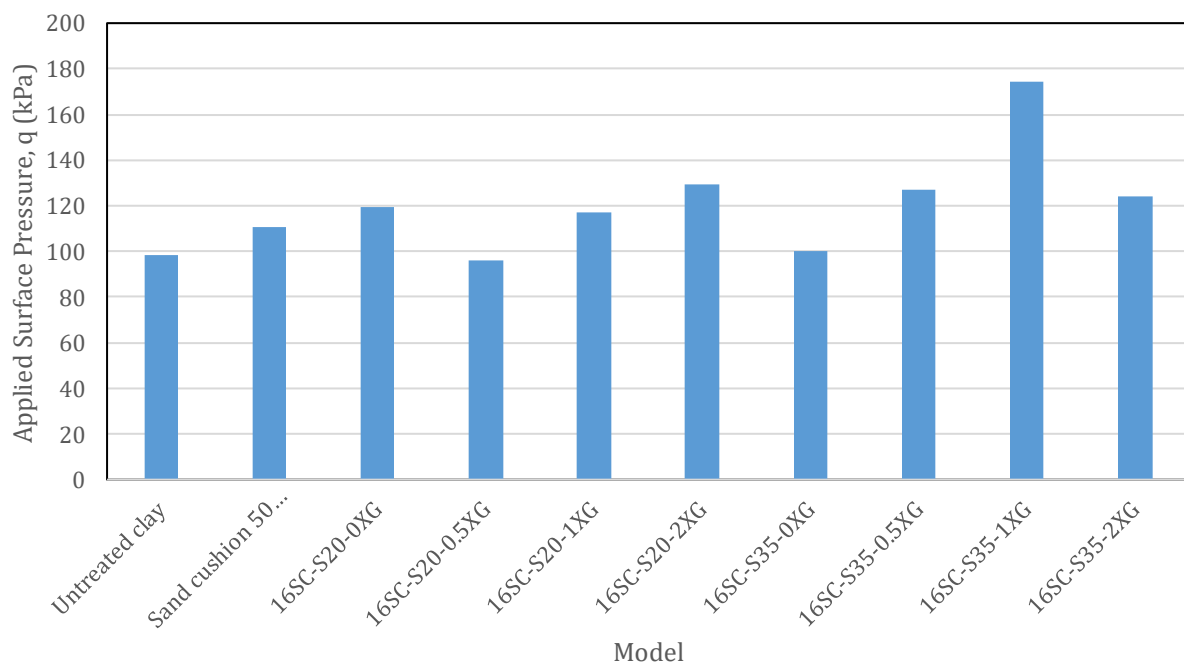


Figure 11. Applied surface pressure at the common comparison settlement of $s/B = 11\%$ for all tested models.

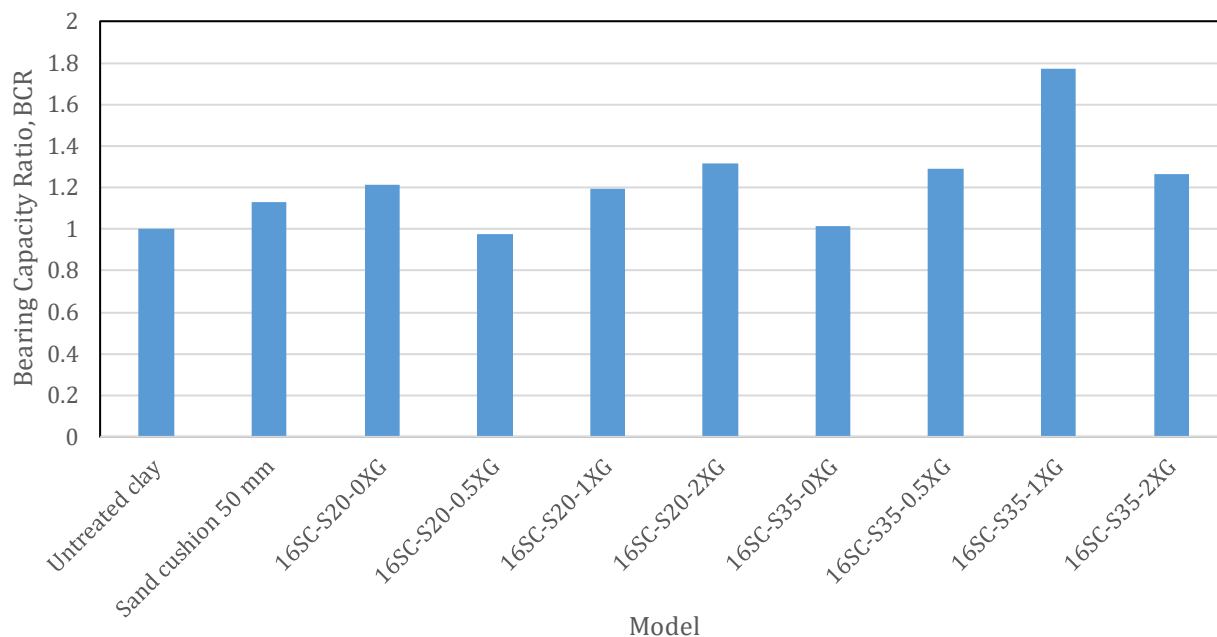


Figure 12. Settlement-based bearing capacity ratio at $s/B = 11\%$ for all tested models.

3.7 Discussion of Xanthan Dosage and Spacing Interaction

The endpoint rankings and pressure–settlement responses indicate a non-monotonic spacing–dosage interaction. The 20 mm clear-spacing array yielded a higher pressure than the 35 mm array for untreated columns, as expected, due to the higher nominal area replacement ratio of the denser array. The spacing effect, however, reversed with dosage after XG addition. The 35 mm array gave the best response at 1% XG, while increasing XG dosage from 1% to 2% reduced the response; however, the 2% case remained above the 0% case., and at 20 mm spacing the highest response was obtained at 2% XG. The reversals suggest that the measured response is not simply monotonic with either nominal column density or XG dosage.

The spacing comparison also includes a change in the overall footprint of the sixteen-column group. When the column number and nominal diameter are fixed, the nominal group width increased from 160 to 205 mm (2.67B to 3.42B) with the increase of clear spacing from 20 to 35 mm. The experimental variable should therefore be understood as array spacing and the geometry of the array groups, and not as a change in inter-column distance under the same treatment footprint. The larger footprint also brings the outer columns closer to the model boundaries, but the minimum nominal group-edge clearances were 4.50B and 4.13B for the 20 and 35 mm arrays, respectively. No boundary-sensitivity series or other group sizes were tested, so the individual effects of inter-column spacing, group footprint, peripheral-column behavior, and residual box restraint cannot be measured.

Possible mechanisms include differences in polymer-bond development, grain contact, moisture redistribution, column stiffness, clay confinement, and column–clay interaction. These mechanisms were not directly measured and are therefore not experimental isolation of causes. The dry-mixing process controlled the nominal XG mass fraction and prevented any visible segregation or agglomeration, but the spatial distribution of XG in the sand was not quantitatively measured. Therefore, the non-monotonic response cannot be ruled out to be due to local polymer-concentration variability. This uncertainty is compounded by the



unconfirmed post-installation column geometry and hydration distribution and makes it difficult to isolate the differences measured from the XG dosage alone.

The diffusion-based screening in Eq. (1) suggests that a characteristic effective diffusivity of $\sim 6.03 \times 10^{-10} \text{ m}^2/\text{s}$ would be needed for a characteristic transport distance of $\sim 12.5 \text{ mm}$ over three days (Dentz et al., 2023). But the real effective diffusivity, hydraulic conductivity, suction and moisture distributions were not measured. The calculation thus does not prove that the column center was hydrated during the conditioning period. The difference in hydration between the outer and inner parts of the column is therefore still a potential source of the measured response.

Finite-box effects also limit separation of the spacing response from the experimental boundary condition. The rigid steel walls could potentially restrict lateral clay deformation and modify confinement of the column group. The general boundary condition was common to all tests, but its influence was not necessarily the same for the two group footprints, since the same box was used throughout. No boundary sensitivity series was performed, and the size of any resulting bias is unknown. The spacing–dosage trends should therefore be interpreted as comparisons between the tested finite model configurations and not as boundary independent column-group behavior.

Another source of uncertainty is initial clay consistency. All models were made from the same material, with the same target water content, placement procedure, and nominal $c_u \approx 17 \text{ kPa}$ condition, but complete model-by-model vane-shear records were not kept. Thus, small variations in the initial strength of the clay cannot be ruled out as a factor in the measured response. This uncertainty further supports the use of the reported pressure differences as descriptive treatment contrasts instead of statistically isolated effects of spacing or XG dosage.

Therefore, the differences measured between the configurations should be considered as the sum of the responses of the models prepared with the given nominal geometries, XG dosages, common installation procedure and equal conditioning duration. The measured response cannot be attributed solely due to spacing or XG dosage, but also to potential installation and hydration variability. This qualification is particularly important for relatively small treatment contrasts. The larger spacing–dosage ranking reversals are still useful descriptive model-scale observations, but the apparent optimum needs to be confirmed by replicated experiments that include direct measurements of installed column geometry, moisture distribution, and treatment uniformity.

3.8 Interaction Contrasts and Statistical Scope

Across the four XG dosages, changing the clear spacing from 20 to 35 mm changed the pressure at $s/B = 11\%$ by -19.540, +30.775, +56.824, and -4.738 kPa for 0%, 0.5%, 1%, and 2% XG, respectively. The change in sign with dosage and the particularly large contrast at 1% XG provide descriptive evidence that the effect of spacing depended on XG dosage rather than following a single monotonic trend.

These values are treatment contrasts and not statistical significance tests because only one bearing test was conducted for each configuration. In addition, although all clay beds were prepared using the same procedure and approximately 17 kPa was used as the target undrained shear strength, replicate pre-test vane measurements were not retained for each model. Exact between-model variability in c_u therefore cannot be quantified. Possible differences in remolded-clay consistency, together with the previously identified



uncertainties in column installation, XG distribution, hydration, and finite boundaries, may contribute to some of the measured differences.

Accordingly, relatively small contrasts should be interpreted cautiously, while the larger changes and reversals in configuration ranking are retained as descriptive model-scale trends. Replicated bearing tests accompanied by documented spatial vane-shear measurements are required before statistical significance or independent treatment effects can be established.

3.9 Comparison with Conventional and Numerical Column Studies

The basic mechanisms of conventional sand and stone columns are the stiffness of the grains, friction, dilation, and confinement of the clay. The effects of a smaller gap or higher percentage of coverage have been reported in published experiments (**Black et al., 2011; Al-Kazzaz and Al-Obaydi, 2021**). The same trend is seen in this study with the untreated columns, with the denser array of $g = 20$ mm outperforming the $g = 35$ mm array. The difference between the bonded infill and the normal stone-column behavior is noted at 0.5% and 1% XG. The numerical studies demonstrate that the stiffness ratio of the column-soil assembly, interface transfer, and a granular blanket have an impact on footing settlement and stress concentration (**Hegde and Sitharam, 2013; Killeen and McCabe, 2014**). The mechanisms are qualitatively consistent with the present interpretation, but no direct numerical validation is claimed as the geometries and constitutive models are different, as are the drainage conditions and the material.

3.10 Durability, Biodegradation, and Groundwater Implications

The present experiments characterize only the short-term bearing response obtained after a three-day covered conditioning period and therefore provide no direct evidence of long-term durability. This distinction is particularly important for XG because its soil-binding response is moisture dependent. Repeated wetting can modify the condition and continuity of hydrated polymer bonds, whereas drying alters water distribution and may increase apparent strength through the development of stronger polymer-particle bonding. Consequently, the short-term resistance measured in the present models should not be assumed to remain unchanged under seasonal or groundwater-induced moisture variations (**Chang et al., 2015; Chen et al., 2019**). Experimental severe-weathering evidence has also demonstrated degradation of mechanical performance in XG-treated soils subjected to repeated environmental exposure (**Lee et al., 2022**).

Long-term application additionally requires consideration of biodegradation and groundwater interaction. XG is an organic polysaccharide; therefore, its persistence in soil can be influenced by biological activity and environmental conditions, while changes in pore-water chemistry may affect polymer hydration, adsorption, viscosity, and interaction with soil particles (**Jang and Jia, 2020; Moghal and Vydehi, 2021**). These mechanisms were not measured in the present investigation, and no conclusions are therefore drawn regarding biodegradation rate, polymer leaching, groundwater compatibility, or retention of bearing improvement with time. Before field implementation, the proposed column system should be evaluated through saturated and cyclic wetting-drying tests, hydraulic conductivity measurements, groundwater-chemistry sensitivity tests, biodegradation and leachate assessments, and sustained or repeated loading under longer conditioning periods. Accordingly, the bearing improvements reported in this study should be interpreted as short-term model-scale performance rather than evidence of durable field stabilization.



4. CONCLUSIONS

The following conclusions apply to the tested model geometry, material preparation, short conditioning interval, loading procedure, and the adopted $s/B = 11\%$ comparison criterion. The latter provides a common normalized deformation level for comparison among the models and is not proposed as a universal ultimate-capacity or field serviceability limit:

- The 50 mm cushion raised pressure from 98.24 to 110.76 kPa. Untreated columns raised it to 119.46 kPa at 20 mm clear spacing but only 99.92 kPa at 35 mm.
- The strongest configuration was 35 mm clear spacing with 1% XG, which reached 174.15 kPa and $BCR = 1.773$. The best 20 mm configuration used 2% XG and reached 129.088 kPa.
- The dosage effect was non-monotonic. Closer spacing or higher XG dosage alone did not guarantee a larger response; Sc/d and XG dosage must be selected together.
- Relative to conventional granular-column trends and published numerical mechanisms, the untreated results are consistent with the benefit of higher replacement ratio, whereas the XG-treated reversals indicate an added bonding and hydration control.

The field application will need to be validated by repeat testing with documented in situ values for clay undrained shear strength, confirmation of actual post-installation column dimensions and contact surface, moisture profile of the column and adjacent clay, pore-water-pressure and suction measurements during loading, hydraulic conductivity of the untreated and XG-treated columns, measured compaction density, other group size and spacing, exposure to wetting and groundwater, and larger models. The reported optimum is therefore provisional and specific to the tested material preparation, nominal geometry, installation procedure, conditioning interval, loading rate, drainage condition, finite boundaries, and model scale rather than general design value. The approximately 17 kPa clay strength was an objective and targeted soil strength preparation condition. It does not imply that the individual beds were statistically equal. The three-day conditioning time is a controlled period. It does not mean that all the material became thoroughly moistened. The slow 1 mm/min loading rate yielded a short-term response; it is not intended to be undrained.

NOMENCLATURE

Symbol	Description	Symbol	Description
A	Footing area, m^2 .	q	Applied surface pressure, kPa.
B	Footing width, mm.	$q_{improved}$	Applied pressure of improved model, kPa.
BCR	Bearing capacity ratio, dimensionless.	$q_{untreated}$	Applied pressure of untreated clay, kPa.
cu	Undrained shear strength, kPa.	S	Footing settlement, mm.
Gs	Specific gravity, dimensionless.	s/B	Settlement ratio, %.
LL	Liquid limit, %.	SO₃	Sulphate content, %.
P	Vertical applied load, N.	TDS	Total dissolved salts, %.
PI	Plasticity index, %.	XG	Xanthan gum (by dry sand mass), %.
PL	Plastic limit, %.	—	—
a_s	Nominal area replacement ratio, %.	D_e	Effective radial moisture diffusivity, m^2/s .
g	Clear edge-to-edge column spacing, mm.	S_c	Center-to-center column spacing, mm.
γ_d	Dry unit weight, kN/m^3 .	d	Column diameter, mm.
De_{re}	Characteristic effective diffusivity required by the radial transport screening calculation, m^2/s	R	Nominal radial transport distance, m
		tc	Conditioning time, s



Credit Authorship Contribution Statement

Malak Jamal Yahya: conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing of the original draft, review and editing, and project administration. Mohammed Y. Fattah: conceptualization, methodology, supervision, validation, and review and editing of the manuscript. Mohammed F. Aswad: conceptualization, methodology, supervision, validation, and review and editing of the manuscript. All authors reviewed and approved the final version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

- Abdelrahman, G.E., Youssef, Y.G., and Abd, M.E., 2026. Experimental study on the improvement of bearing capacity of soft clay by using reinforced sand cushion resting on encased stone columns. *HBRC Journal*, 22(1), pp. 36–51. <https://doi.org/10.65800/2090-9934.1003>
- Alavi, S.M., Shakeri Talarposhti, S., Khodaei Ardabili, A.A., and Aghamolaei, M., 2024. Field study on unconfined compressive strength and drilling data of DSM columns: a machine learning approach. In *International Conference on Transportation and Development 2024: Transportation Safety and Emerging Technologies*, Atlanta, GA, USA, 15–20 June 2024, pp. 404–416. Reston, VA: American Society of Civil Engineers. <https://doi.org/10.1061/9780784485514.036>
- Al-Hashemi, H.M.B., 2016. Bearing capacity and settlement of shallow foundation: Comparison of different approaches. Term Project Report, Master of Science in Geotechnical Engineering, Civil and Environmental Engineering Department, College of Engineering Sciences and Applied Engineering, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia. <https://doi.org/10.13140/RG.2.2.23244.82560>
- Al-Kaisi, A.R., and Ali, H.H., 2013. Mathematical estimation for the bearing capacity of sand column inserted in soft clay soil. *Engineering and Technology Journal*, 31(5A), pp. 816–827. <https://doi.org/10.30684/etj.31.5a2>
- Al-Kazzaz, Z.A., and Al-Obaydi, M.A., 2021. Effect of spacing between stone columns on the behavior of soft soil. *E3S Web of Conferences*, 318, Article 01006. <https://doi.org/10.1051/e3sconf/202131801006>
- Al-Kubaisi, O.K.I., 2018. Prediction of the effect of using stone column in clayey soil on the behavior of circular footing by ANN model. *Journal of Engineering*, 24(5), pp. 86–97. <https://doi.org/10.31026/j.eng.2018.05.06>
- Al-Saoudi, N.K.S., Al-Kaissi, M.M.M., and Al-Baiaty, S.E.K., 2013. Ordinary and encased stone columns with two different relative densities. *Engineering and Technology Journal*, 31(13A), pp. 2415–2432. <https://doi.org/10.30684/etj.31.13a.2>
- Al-Subari, B.L., Hilal, A., and Ekinici, A., 2023. Life cycle assessment of soil stabilization using cement and waste additives. *Construction and Building Materials*, 403, Article 133045. <https://doi.org/10.1016/j.conbuildmat.2023.133045>



- Andreou, P., Frikha, W., Frank, R., Canou, J., Papadopoulos, V., and Dupla, J.C., 2008. Experimental study on sand and gravel columns in clay. *Proceedings of the Institution of Civil Engineers – Ground Improvement*, 161(4), pp. 189–198. <https://doi.org/10.1680/grim.2008.161.4.189>
- Askari, F., Gharib, M., Ranjbar Malidarreh, N., Esmailnia Amiri, M., and Soleimani Kutanaei, S., 2025. Investigation of self-healing process and strength of biopolymer-stabilized silty sand: Comparison of xanthan and Persian gum in geotechnical engineering. *Carbohydrate Polymer Technologies and Applications*, 11, Article 100914. <https://doi.org/10.1016/j.carpta.2025.100914>
- ASTM D1143/D1143M, 2020. Standard Test Methods for Deep Foundation Elements Under Static Axial Compressive Load. West Conshohocken, PA: ASTM International.
- ASTM D422, 2007. Standard test method for particle-size analysis of soils.
- ASTM D854, 2014. Standard test methods for specific gravity of soil solids by water pycnometer.
- ASTM D2974, 2014. Standard test methods for moisture, ash, and organic matter of peat and other organic soils.
- ASTM D4318, 2017. Standard test methods for liquid limit, plastic limit, and plasticity index of soils.
- ASTM D4972, 2019. Standard test methods for pH of soils.
- ASTM D5907, 2018. Standard test methods for filterable matter (total dissolved solids) and nonfilterable matter (total suspended solids) in water.
- Barman, D., and Dash, S.K., 2022. Stabilization of expansive soils using chemical additives: a review. *Journal of Rock Mechanics and Geotechnical Engineering*, 14(4), pp. 1319–1342. <https://doi.org/10.1016/j.jrmge.2022.02.011>
- Bergado, D.T., Balasubramaniam, A.S., Fannin, R.J., and Holtz, R.D., 2002. Prefabricated vertical drains (PVDs) in soft Bangkok clay: a case study of the new Bangkok International Airport project. *Canadian Geotechnical Journal*, 39(2), pp. 304–315. <https://doi.org/10.1139/t01-100>
- Black, J.A., Sivakumar, V., and Bell, A., 2011. The settlement performance of stone column foundations. *Géotechnique*, 61(11), pp. 909–922. <https://doi.org/10.1680/geot.9.p.014>
- Chang, I., Im, J., Prasadhi, A.K., and Cho, G.C., 2015. Effects of xanthan gum biopolymer on soil strengthening. *Construction and Building Materials*, 74, pp. 65–72. <https://doi.org/10.1016/j.conbuildmat.2014.10.026>
- Chen, C., Wu, L., Perdjon, M., Huang, X., and Peng, Y., 2019. The drying effect on xanthan gum biopolymer treated sandy soil shear strength. *Construction and Building Materials*, 197, pp. 271–279. <https://doi.org/10.1016/j.conbuildmat.2018.11.120>
- Debnath, P., and Dey, A.K., 2017. Bearing capacity of reinforced and unreinforced sand beds over stone columns in soft clay. *Geosynthetics International*, 24(6), pp. 575–589. <https://doi.org/10.1680/jgein.17.00024>
- Dentz, M., Hidalgo, J.J. and Lester, D., 2023. Mixing in porous media: Concepts and approaches across scales. *Transport in Porous Media*, 146, pp. 5–53. <https://doi.org/10.1007/s11242-022-01852-x>
- Díaz, E., Salamanca-Medina, E.L., and Tomás, R., 2024. Assessment of compressive strength of jet grouting by machine learning. *Journal of Rock Mechanics and Geotechnical Engineering*, 16(1), pp. 102–111. <https://doi.org/10.1016/j.jrmge.2023.03.008>



- Dutta, R.K., Khatri, V., Sharma, A., and Gayathri, V., 2025. Performance of square footing resting on clay reinforced with granular columns. *Transportation Infrastructure Geotechnology*, 12(6), Article 189. <https://doi.org/10.1007/s40515-025-00640-6>
- Fattah, M.Y., Shlash, K.T., and Al-Waily, M.J.M., 2011. Stress concentration ratio of model stone columns in soft clays. *Geotechnical Testing Journal*, 34(1), pp. 50–60. <https://doi.org/10.1520/gtj103060>
- Foye, K.C., Basu, P., and Prezzi, M., 2008. Immediate settlement of shallow foundations bearing on clay. *International Journal of Geomechanics*, 8(5), pp. 300–310. [https://doi.org/10.1061/\(ASCE\)1532-3641\(2008\)8:5\(300\)](https://doi.org/10.1061/(ASCE)1532-3641(2008)8:5(300))
- Hegde, A., and Sitharam, T.G., 2013. Experimental and numerical studies on footings supported on geocell reinforced sand and clay beds. *International Journal of Geotechnical Engineering*, 7(4), pp. 346–354. <https://doi.org/10.1179/1938636213Z.000000000043>
- Hughes, J.M.O., and Withers, N.J., 1974. Reinforcing of soft cohesive soils with stone columns. *Ground Engineering*, 7(3), pp. 42–49.
- Inazumi, S., and Shakya, S., 2024. A comprehensive review of sustainable assessment and innovation in jet grouting technologies. *Sustainability*, 16(10), Article 4113. <https://doi.org/10.3390/su16104113>
- Jang, J., and Jia, P., 2020. A review of the application of biopolymers on geotechnical engineering and the strengthening mechanisms between typical biopolymers and soils. *Advances in Materials Science and Engineering*, 2020, Article 1465709. <https://doi.org/10.1155/2020/1465709>
- Jayarajan, J., and Karpurapu, R., 2021. Bearing capacity and settlement response of ordinary and geosynthetic encased granular columns in soft clay soils: analysis and design charts. *Indian Geotechnical Journal*, 51(2), pp. 237–253. <https://doi.org/10.1007/s40098-020-00457-9>
- Killeen, M.M., and McCabe, B.A., 2014. Settlement performance of pad footings on soft clay supported by stone columns: a numerical study. *Soils and Foundations*, 54(4), pp. 760–776. <https://doi.org/10.1016/j.sandf.2014.06.011>
- Kitazume, M., and Terashi, M., 2013. *The Deep Mixing Method*. London: CRC Press. <https://doi.org/10.1201/b13873>
- Kravchenko, E., Lu, W., Sauerwein, M., and Wong, A.H.K., 2024. Life cycle assessment of waste materials in deep cement mixing for land reclamation in Hong Kong. *Environmental Impact Assessment Review*, 105, Article 107398. <https://doi.org/10.1016/j.eiar.2023.107398>
- Lee, M., Kwon, Y.-M., Park, D.-Y., Chang, I., and Cho, G.-C., 2022. Durability and strength degradation of xanthan gum based biopolymer treated soil subjected to severe weathering cycles. *Scientific Reports*, 12, Article 19453. <https://doi.org/10.1038/s41598-022-23823-4>
- Lopez, M., and Quevedo, R., 2022. Modeling of settlement and bearing capacity of shallow foundations in overconsolidated clays. *Journal of GeoEngineering*, 17(1), Article 1. [https://doi.org/10.6310/jog.202203_17\(1\).1](https://doi.org/10.6310/jog.202203_17(1).1)
- Mach, A., and Szczygielski, M., 2024. Carbon footprint analysis throughout the life cycle of the continuous deep mixing method (CDMM) technology. *Energies*, 17(13), Article 3294. <https://doi.org/10.3390/en17133294>



- Mehrannia, N., Nazariafshar, J., and Kalantary, F., 2018. Experimental investigation on the bearing capacity of stone columns with granular blankets. *Geotechnical and Geological Engineering*, 36(1), pp. 209–222. <https://doi.org/10.1007/s10706-017-0317-6>
- Moghal, A.A.B., and Vydehi, K.V., 2021. State-of-the-art review on efficacy of xanthan gum and guar gum inclusion on the engineering behavior of soils. *Innovative Infrastructure Solutions*, 6(2), Article 108. <https://doi.org/10.1007/s41062-021-00462-8>
- Mohammed, S.M., 2015. The effect of granular material on behaviour of stone columns in soft clay under embankment. *Engineering and Technology Journal*, 33(9A), pp. 2212–2219. <https://doi.org/10.30684/etj.2015.116242>
- Ni, J., Hao, G.L., Chen, J.Q., Ma, L., and Geng, X.Y., 2021. The optimisation analysis of sand–clay mixtures stabilised with xanthan gum biopolymers. *Sustainability*, 13(7), Article 3732. <https://doi.org/10.3390/su13073732>
- Sabermahani, M., and Hajisalimi, A., 2025. Field study on jet grouting columns performance above and below groundwater table in sandy soil. *Case Studies in Construction Materials*, 23, Article e05105. <https://doi.org/10.1016/j.cscm.2025.e05105>
- Sakleshpur, V.A., Prezzi, M., and Salgado, R., 2018. Ground engineering using prefabricated vertical drains: a review. *Geotechnical Engineering Journal of the SEAGS & AGSSEA*, 49(1), pp. 45–64. <https://doi.org/10.14456/seagi.2018.54>
- Staubach, P., Macháček, J., Bienen, B., and Wichtmann, T., 2022. Long-term response of piles to cyclic lateral loading following vibratory and impact driving in water-saturated sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 148(11), Article 04022097. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0002906](https://doi.org/10.1061/(ASCE)GT.1943-5606.0002906)
- Stuedlein, A.W., and Holtz, R.D., 2013. Bearing capacity of spread footings on aggregate pier reinforced clay. *Journal of Geotechnical and Geoenvironmental Engineering*, 139(1), pp. 49–58. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000748](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000748)
- Wu, Y., Zhang, Y., Qiu, J., Li, Y., and Xia, S., 2025. pH and hardness of cement-stabilized soil leachate under the influence of multiple factors. *Advances in Cement Research*, 37(12), pp. 645–653. <https://doi.org/10.1680/jadcr.24.00140>
- Xin, Y., Ding, X., Zhao, J., Wang, H., and Jiang, C., 2025. A study on the response of coral sand foundations with different particle gradations reinforced using a vibroflotation method. *Journal of Marine Science and Engineering*, 13(4), Article 666. <https://doi.org/10.3390/jmse13040666>
- Zhao, K., and Wong, L.N.Y., 2025. A review of cement-soil in engineering geological applications: mixing mechanisms, mechanical behavior, and constitutive models. *Bulletin of Engineering Geology and the Environment*, 84(12), Article 637. <https://doi.org/10.1007/s10064-025-04659-4>

تأثير المسافة بين الأعمدة ومحتوى صمغ الزانثان الجاف على استجابة التحمل للطين الطري المُحسَّن بالأعمدة الرملية

ملاك جمال يحيى*، محمد يوسف فتاح، محمد فائق اسود

قسم هندسة الطرق والجيو تكنك، كلية الهندسة المدنية، الجامعة التكنولوجية، بغداد، العراق

الخلاصة

تتعرض الأساسات المقامة على الطين الرخو عادةً إلى انخفاض مقاومة التحمل وزيادة الهبوط، في حين يعتمد أداء أنظمة الأعمدة الحبيبية على كلٍ من هندسة الأعمدة وخصائص مادة الحشو. تهدف هذه الدراسة إلى التحقق تجريبياً من التأثير المشترك للمسافة بين الأعمدة ومحتوى صمغ الزانثان (XG) المخلوط جافاً في استجابة التحمل للطين الرخو المحسَّن بوسادة رملية بسمكة 50 ملم ومجموعة 4 × 4 من الأعمدة الرملية. أُجريت الاختبارات المختبرية داخل صندوق فولاذي صلب بأبعاد 700 × 700 × 800 ملم باستخدام أساس مربع بأبعاد 60 × 60 ملم. حُضِّرت طبقات الطين عند محتوى مائي مستهدف يقارب 25% ومقاومة قص غير ميزولة مستهدفة تقارب 17 كيلوباسكال. استُخدم ستة عشر عموداً رملياً بقطر 25 ملم وطول 150 ملم، وبمسافتين صافيتين بين الأعمدة مقدارهما 20 و 35 ملم، تقابلان نسبتي تباعد مركزي إلى القطر (Sc/d) مقدارهما 1.80 و 2.40، على التوالي. دُرست محتويات من صمغ الزانثان مقدارها 0% و 0.5% و 1% و 2% من كتلة الرمل الجاف بعد فترة تكييف مغطاة وموحدة مدتها ثلاثة أيام. وقورنت الاستجابات عند نسبة هبوط $s/B = 11\%$ بلغ الضغط المسجل للطين غير المحسَّن 98.24 كيلوباسكال، وارتفع باستخدام الوسادة الرملية إلى 110.76 كيلوباسكال. تحققت أعلى استجابة عند مسافة 35 ملم ومحتوى 1% من صمغ الزانثان، إذ بلغ الضغط 174.15 كيلوباسكال ونسبة قدرة التحمل 1.773 (BCR) أما عند مسافة 20 ملم، فتحققت أفضل استجابة عند محتوى 2% من صمغ الزانثان، بضغط بلغ 129.088 كيلوباسكال ونسبة قدرة تحمل مقدارها 1.314. أظهرت النتائج وجود تفاعل غير رتيب بين تباعد الأعمدة ومحتوى صمغ الزانثان، مما يؤكد أن تقليل المسافة بين الأعمدة أو زيادة محتوى الزانثان بصورة منفردة لا يضمن بالضرورة تحسناً في استجابة التحمل. لذلك، تُعد الحالة المثلى المحددة خاصة بظروف النموذج المختبر، وتحتاج إلى تأكيد من خلال اختبارات مكررة وعلى نماذج أكبر حجماً.

الكلمات المفتاحية: الطين الرخو، الأعمدة الرملية، صمغ الزانثان، تباعد الأعمدة، نسبة قدرة التحمل، تحسين التربة.