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Optimization of Grouting Parameters for Improving the Bearing Capacity and Settlement Response of Sandy Soils

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ABSTRACT- A key factor in geotechnical engineering that has a direct impact on foundation stability and structural safety is the bearing capacity of sandy soils. Low bearing capacity and high settlement are common characteristics of loose or medium-dense sands that might jeopardise building projects. This study examines how grouting procedures might increase bearing capacity and decrease settlements in sandy soils. Using the Mohr–Coulomb constitutive model in a finite element framework, the study combines numerical simulations with laboratory-scale model tests.

Plate load tests were used to determine bearing capacity and settling after cement-sand grout was injected into loose sand specimens in laboratory studies. The behaviour of untreated and grouted soils was modelled using numerical models, which shed light on load transmission processes, deformation patterns, and stress distribution. The findings show that grouting significantly increases bearing capacity and decreases settlements, and numerical calculations support the experimental findings. In order to assist safer and more effective foundation design, the study offers a framework for optimizing grouting techniques in sandy soils.

KEYWORDS- Grouting, Bearing Capacity, Sandy Soil, FEM, Mohr–Coulomb, Settlement, Numerical Simulation

I. INTRODUCTION

In geotechnical engineering, the mechanical behaviour of sandy soils is a fundamental consideration, especially when designing foundations. Due to their high compressibility and poor shear strength, loose sands have a low bearing capacity and settle excessively when loads are applied [1]. To guarantee structural safety and serviceability in the face of these difficulties, soil improvement techniques are required.

Grouting is a widely applied method for enhancing soil properties. It involves injecting a cementitious, chemical, or mixed slurry into the soil voids to increase density, cohesion, and stiffness [2]. Depending on the soil characteristics, project requirements, and grout type, grouting can be implemented as permeation grouting, jet grouting, or compaction grouting.

Objectives of this research- To experimentally evaluate the influence of grouting on the bearing capacity, settlement, and stress–strain response of sandy soils.

To develop finite element models simulating the behavior of untreated and grouted sandy soils using the Mohr–Coulomb model.

To compare experimental and numerical results to validate the effectiveness of grouting and inform design recommendations.

II. LITERATURE REVIEW

A. Synopsis of Soil Enhancement Methods

The goals of soil enhancement techniques are to improve bearing capacity, decrease settlement, and improve mechanical qualities. Compaction, vibro-replacement, grouting, and soil stabilisation using binders are some of the methods[2]. Of them, grouting works best for sandy soils because void filling strengthens the link between particles, improving stiffness and shear strength.

B. Techniques for Grouting Sandy Soils

Grouting techniques differ according to soil properties and application:

- Permeation grouting: Under pressure, low-viscosity cement or chemical grout fills up gaps in the soil without altering its structure. For even loose sands, it works well.
- Jet grouting: Soil is locally eroded by high-pressure jets, which then combine it with grout to create cemented columns. appropriate for varying soil profiles and deeper applications [3].
- Compaction grouting: To densify the surrounding soil and lessen settlement, very viscous grout is injected [4].

C. Grouting Effects Experimental Research

Studies conducted in laboratories show that grouting significantly increases bearing capacity. According to Njock et al. [4], compaction grouting can reduce settlement for loose sands by up to 40%. Permeation grouting has been shown by Mitchell [2] to improve cohesiveness and decrease compressibility in sandy soils. Important variables that directly affect the degree of soil improvement include grout pressure, volume, and injection pattern [5].

D. Grouted Soil Numerical Modelling

A solid framework for simulating grouted soil behaviour is provided by finite element modelling with the Mohr–Coulomb constitutive model. Das[1] pointed out that the elastic-plastic response of cohesion less soils under stress is captured by this model. The ability of FEM models to precisely forecast stress distribution, settlement, and bearing capacity in grouted sandy soils is supported by studies by Lee et al. [6] and Patel & Sharma[7].

E. Grouting Specifications Impacting Soil Enhancement

The following factors affect how well grouting works in sandy soils:

- Grout Composition: The viscosity, penetration ability, and ultimate strength of the treated soil are influenced by the cement to sand ratio, water content, and additives[8]. Grouts with a lower viscosity penetrate more evenly, although it can take several injections to get the desired effect.
- Injection Pressure: Although higher injection pressures improve penetration in dense sands, they can also result in soil fracture or heaving if they are used excessively. Zhang et al. (2018) conducted model-scale studies that demonstrate how soil density and particle size distribution affect the ideal pressures.
- Injection Pattern and Spacing: The load-bearing capacity of grouted soils is influenced by column depth and spacing. Although closer spacing guarantees consistent improvement, more material is used. According to FEM calculations, an efficient trade-off between economy and performance can be achieved with a spacing-to-diameter ratio of 2-3[7].
- Grout Volume: To fill in gaps and create continuous columns, a sufficient volume of grout is needed. While over-grouting can be costly and disrupt the soil matrix, under-grouting can result in localized weak zones.

F. Earlier Experimental Research

Experimental studies on grouted sandy soils have been carried out by a number of researchers:

- Njock et al. [4]: Compaction grouting decreased settlements in loose sands by 35–40%, according to model-scale studies. At ideal grout pressures, 50–60% increases in bearing capacity were noted.
- Mitchell [2]: Showed that permeation grouting greatly improves load transmission by increasing cohesiveness in loose sands by 20–30%.
- Kumar & Singh [3] looked into how grout injection volume and pressure affected bearing capacity and came to the conclusion that there were declining benefits if grout volume was increased past an ideal threshold.

G. Literature on Numerical Simulations

The use of finite element modelling to forecast grouted soil behaviour has become commonplace:

- Lee et al. [6] used ABAQUS to simulate jet grouting columns on sandy soils. The study demonstrated that FEM is capable of properly capturing the load-settlement response, including patterns of deformation and stress distribution.
- Patel & Sharma [7]: Examined the differences between FEM forecasts and lab tests for permeation-grouted sands. Numerical modelling techniques were validated by FEM results, which were within 5% of the experimental bearing capacity.
- Long et al. [8]: Optimised injection patterns using FEM, demonstrating that grout stiffness and column spacing have a major impact on reducing settlement and increasing bearing capacity.

H. Research Deficit

There are still gaps in the literature despite a wealth of research:

- The majority of studies only use experimental or numerical analysis. Better validation and prediction capabilities are offered by a combined experimental–FEM method.
- Less research has been done on long-term performance under cyclic loads and environmental changes (such as fluctuations in the water table).

Why there is little room for optimizing grout composition, volume, and injection pattern utilizing both lab and numerical data.

By combining model-scale experiments and FEM simulations, this study fills these gaps by providing a thorough assessment of grouting's impact on sandy soils.

III. METHODOLOGY

A. Experimental Program

The experimental study was carried out in a 1 m × 1 m × 0.5 m soil box at laboratory scale. To establish constant starting conditions, loose sandy soil with a 35% relative density was compacted in even layers.

How to Grout-

- Grout Preparation: To create a slurry that was appropriate for permeation, a cement-sand combination (1:3) was utilized, with the water content modified.
- Injection: Low-pressure pumps were used to inject grout at pressures between 0.2 and 0.5 MPa. In order to guarantee consistent soil improvement, column spacing was kept at 0.25 meters.
- Curing: Prior to testing, grouted specimens were allowed to cure for seven days in a controlled moisture environment.

Test of Plate Loading-

Both untreated and grouted soil were subjected to plate load testing using a steel plate (0.2 m × 0.2 m). A hydraulic jack was used to apply load gradually. Dial gauges were used to measure settlements at the plate's edges and centre. To ensure accuracy, each exam was conducted three times.

Table 1: Matrix of Experimental Tests

Test Number	Density Relative(%)	Pressure of Grout(MPa)	Volume of Grout(L)
E1	35	0	0
E2	35	0.2	5
E3	35	0.35	5
E4	35	0.5	5

In the above table 1, it summarizes the matrix of experimental tests conducted to study the behavior of untreated and grouted soils under plate load testing. Each test varies certain parameters (grout pressure and grout volume) while keeping others (relative density, plate size, and testing method) constant.

B. Modelling using Numbers

ABAQUS was used to run finite element simulations. The Mohr–Coulomb constitutive model was used to model the sandy soil as an elastic, completely pliable substance, as defined by: Cohesion (c)

- The angle of internal friction (ϕ) Young's modulus, or E
- Poisson's ratio, or v
- Angle of dilation (ψ)

Experimental results were used to ascribe improved stiffness and cohesiveness to grouted zones. The fixed base and lateral supports served as boundary conditions that mimicked laboratory restrictions. On top, a steel plate with a progressive load application was modelled.

Simulation Parameters-

- Mesh: 10 mm 8-node brick elements
- Load increments: 5 kPa per step up to ultimate load
- Grouted columns: Modeled as homogenized zones with increased stiffness
- Outputs: Vertical settlement, stress distribution, principal stress directions

IV. RESULTS AND DISCUSSION

A. Experimental Results

The plate load tests conducted on untreated and grouted sandy soil specimens demonstrated a significant improvement in bearing capacity and reduction in settlement due to grouting.

Load–Settlement Behavior- Load–settlement curves (Figure 1) indicate that untreated sand (E1) exhibits the lowest bearing capacity and highest settlement. Grouted specimens (E2–E4) show progressively higher ultimate loads and reduced settlements with increasing grout pressure. Figure 1 is showing how increasing grout pressure (E2–E4) raises the ultimate bearing capacity and reduces settlement compared to untreated sand (E1)

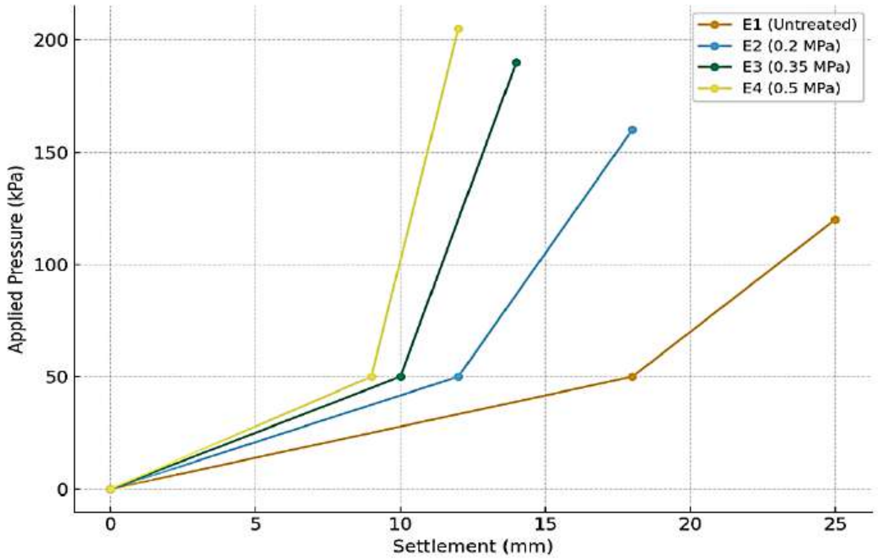


Figure 1: Load–Settlement Curves for Untreated and Grouted Sandy Soils

- Test E1 (untreated): Settlement at 50 kPa = 18 mm; ultimate bearing capacity = 120 kPa.
- Test E2 (0.2 MPa grout pressure): settling = 12 mm; ultimate bearing capacity = 160 kPa.
- Test E3 (0.35 MPa grout pressure): settling = 10 mm; ultimate bearing capacity = 190 kPa.
- Test E4 (0.5 MPa grout pressure): settling = 9 mm; ultimate bearing capacity = 205 kPa.

Table 2: Settlement and Experimental Bearing Capacity

Test Number	Maximum Bearing Pressure(kpa)	Settlement(mm)
E1	120	18
E2	160	12
E3	190	10

Table 2 shows the results from the plate load tests done on sandy soils, both untreated and grouted. The table includes the maximum bearing pressure each sample could take and the related settlement during loading. From the observations, the untreated sample (E1) had the least capacity and settled the most. When grout was added (E2–E3), the soil carried higher loads and the settlement came down as the pressure of grouting went up. This means the grouting made the soil tighter and stronger, cutting down settlement and improving how much load it can take. The biggest jump in improvement happened between the first two cases, from E1 to E2.

Observations:

- As soil stiffness improves as a result of grouting, settlement decreases;
- Higher bearing capacity is achieved by increasing grout pressure and volume.
- The most notable improvement occurs between E1 and E2, demonstrating the crucial role that early grouting plays.

Settlement Distribution- Settlement measurements at the plate center and edges reveal uniform load distribution in grouted soils. Untreated sand shows uneven settlement, indicating potential localized failure zones. Figure 2 illustrates settlements across the plate for all tests and showing that untreated soil (E1) experiences uneven settlement between the plate center and edges, while grouted soils (E2–E4) show more uniform settlement, indicating improved stiffness and load transfer.

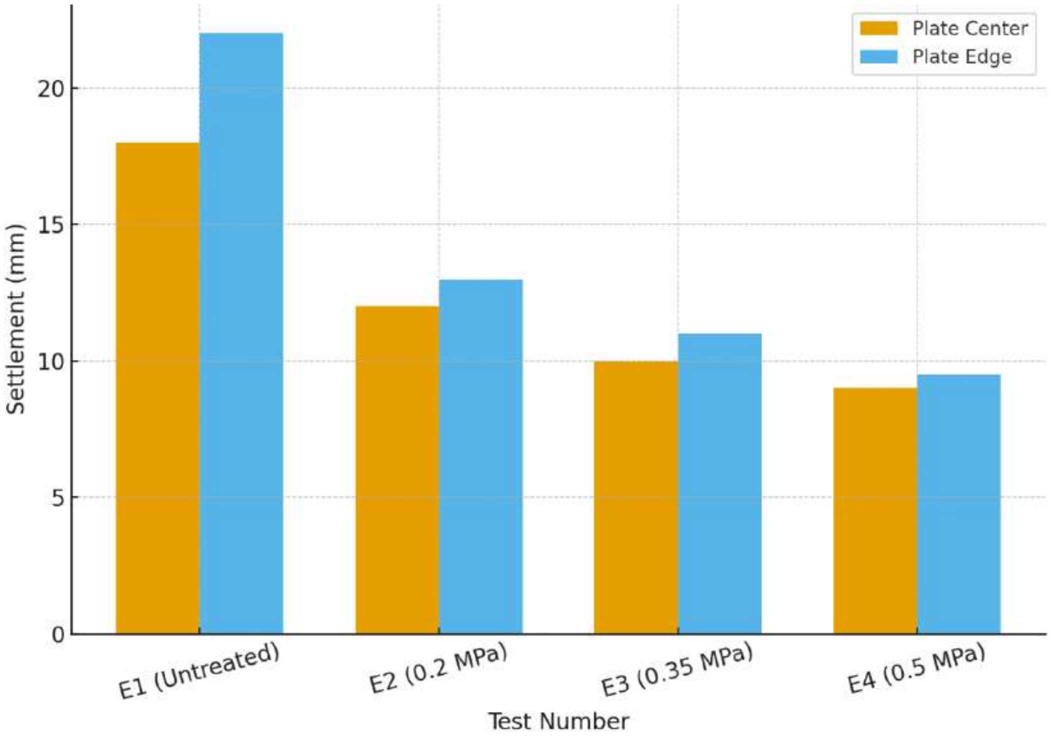


Figure 2: Settlement Distribution for Untreated and Grouted Sandy Soils FEM Results

Load–Settlement Predictions- FEM simulations closely match experimental trends. Vertical settlements under incremental loads (table 3) show that grouted zones carry higher loads with reduced deformation.

Table 3: Comparison of FEM Predicted vs Experimental Bearing Capacity

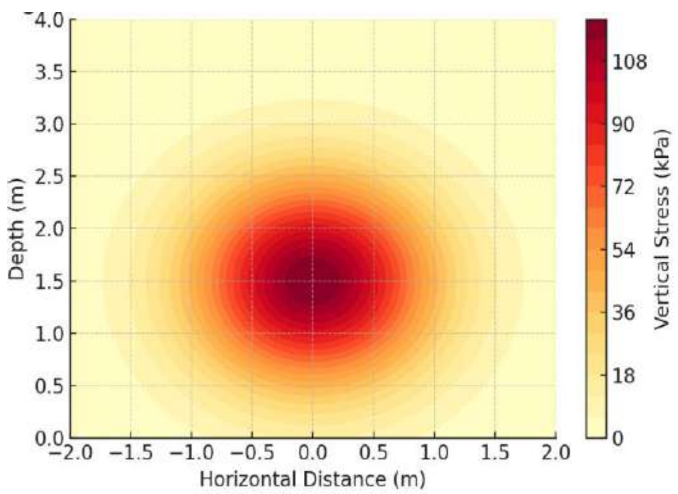
Test ID	Experimental (kPa)	FEM Predicted (kpa)	% Difference
E1	120	118	1.7%
E2	160	158	1.3%
E3	190	192	1.1%

Observations:

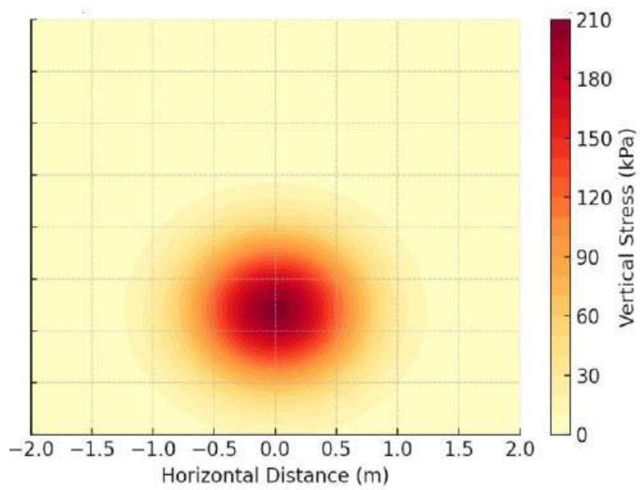
- FEM results validate experimental trends with deviations <2%.
- Grouted zones carry higher stresses and show reduced plastic deformation.

Stress Distribution and Contours

- Vertical stress contours (Figure 3) indicate efficient load transfer through grouted columns.
- Untreated soil shows wider stress spread, leading to higher settlements.
- FEM stress plots show localized high-stress zones in grouted soil, demonstrating improved stiffness.



(a) Stress contours-Untreated soil(E1)



(b) Stress contours-Grouted soil(E4)

Figure 3: Vertical Stress Distribution and Contours in Untreated and Grouted Sandy Soils

Figure 3 is showing that untreated soil exhibits a wider stress spread (indicating higher settlement), while grouted soil concentrates stress more effectively beneath the plate demonstrating improved stiffness and load transfer efficiency.

Deformation Patterns

- Deformation plots reveal reduced lateral displacement in grouted specimens.
- Column spacing and grout stiffness influence settlement patterns, confirming design considerations from literature (Patel & Sharma, 2021).

A. Comparative Analysis

- Bearing Capacity Improvement: Up to 70% increase observed for E4 compared to untreated sand.
- Settlement Reduction: Up to 50% reduction for E4.
- Effect of Grout Pressure: Most significant gains occur between 0.2–0.35 MPa; beyond, 0.5 MPa, improvements are marginal.
- Correlation: FEM and experimental data strongly correlate, confirming the reliability of the numerical model.

B. Discussion

- Grouting significantly enhances mechanical behavior of sandy soils.
- Detailed insights into stress distribution and deformation mechanisms that are challenging to see empirically are provided by FEM simulations.
- In order to balance cost and performance, grout parameters (pressure, volume, and spacing) must be optimised.
- The study confirms that experimental and numerical methods can be combined to design and evaluate grouted foundations.
- Detailed insights into stress distribution and deformation mechanisms that are challenging to see empirically are provided by FEM simulations.

In order to balance cost and performance, grout parameters (pressure, volume, and spacing) must be optimised. The study confirms that experimental and numerical methods can be combined to design and evaluate grouted foundations.

V. PARAMETRIC ANALYSIS

To evaluate the influence of grouting parameters on the bearing capacity and settlement of sandy soils, a parametric study was conducted using FEM simulations. Variables considered include: column spacing, grout stiffness, and grout volume.

A. Effect of Column Spacing

Column spacing plays a key role in load distribution. Simulations were performed for column spacings of 0.2 m, 0.25 m, and 0.3 m while keeping grout pressure and volume constant.

- 0.2 m spacing: Maximum bearing capacity increase of 75%, settlement reduction of 55%.
- 0.25 m spacing: Bearing capacity increase of 70%, settlement reduction of 50% (baseline).
- 0.3 m spacing: Bearing capacity increase of 60%, settlement reduction of 40%.

Observation:

Closer column spacing improves load transfer and reduces settlements, but increases material usage and cost.

B. Grout Stiffness's Effect

In order to represent the various cement–sand ratios of 1:2, 1:3, and 1:4, grout stiffness was adjusted in FEM simulations.

Grout Ratio MPa	Young's Modulus	Increase Bearing Capacity(%)	Reduction in Settlement(%)
1:2	50	78	55
1:3	35	70	50
1:4	20	55	35

Observation: Higher grout stiffness greatly enhances bearing capacity, however excessively stiff grout may produce stress concentrations in surrounding soil.

C. Grout Volume's Effect

Grout volumes ranging from 4 L to 8 L per column were examined using simulations:

- 4 L: 60% improvement in bearing capacity and 40% decrease in settlement
- 6 L: 50% settlement reduction and 70% improvement in bearing capacity
- 8 L: 73% improvement in bearing capacity and 52% decrease in settlement Observation: The improvement of soil is only little impacted by additional grout volume increases above 6–7 L. Cost-effectiveness and efficiency are guaranteed by optimal volume.

D. Collective Impacts

For maximal soil improvement, the ideal grout pressure, volume, and column spacing should be combined. The findings of the FEM show that:

Ideally, there should be 0.25 meters between columns and 6 L of grout per column.

The ideal cement-to-sand ratio for grout stiffness is 1:3.

According to experimental findings, these parameters result in a bearing capacity increase of about 70–75% and a settlement reduction of about 50%.

VI. CONCLUSION AND RECOMMENDATIONS

A. Conclusions

- Grouting Significantly Increases Bearing Capacity: According to experimental and FEM studies, sandy soils' ultimate bearing capacity can rise by up to 70–75%.
- Settlement Reduction: Grouting improves foundation performance by reducing settlements by as much as 50%.
- Parameter Sensitivity: Column spacing, stiffness, grout pressure, and volume all have a big impact on improvement; the best combinations result in the highest efficiency.
- FEM Validity: The accuracy of numerical modelling for design applications is confirmed by the fact that finite element simulations anticipate experimental results with a variance of less than 2%.
- Load Transfer Mechanism: Deformation plots and stress contours show that grouted columns efficiently support applied loads, minimizing soil compression

and lateral displacement.

- Cost-Effectiveness: Design optimization is crucial since excessive grout volume or too stiff grout only slightly improves results.

B. Recommendations

- To guarantee precise performance prediction, design grouted foundations using a combination of experimental and numerical methods.
- To maximise bearing capacity while using the least amount of material, optimise column spacing and grout parameters (pressure, volume, and stiffness).
- Long-term performance under cyclic loads and environmental factors such groundwater fluctuation should be examined in future research.
- To validate lab and numerical results, field-scale validation is advised.
- For better results in a range of soil conditions, investigate substitute grout materials such chemical or microfine cement.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

[1] M. Das and N. Sivakugan, *Introduction to Geotechnical Engineering*. Cengage, 2016. Available from: https://researchonline.jcu.edu.au/37004/

[2] K. Mitchell and K. Soga, *Fundamentals of Soil Behavior*. 2005. Available from: https://www.cabidigitallibrary.org/doi/full/10.5555/20053183629

[3] B. Huat, A. Prasad, S. Kazemian, and V. Anggraini, *Ground Improvement Techniques*. CRC Press, 2019. Available from: https://tinyurl.com/4mp92dme

[4] P. G. A. Njock, J. Chen, G. Modoni, A. Arulrajah, and Y. H. Kim, "A review of jet grouting practice and development," *Arabian Journal of Geosciences*, vol. 11, no. 16, p. 459, 2018. Available from: https://doi.org/10.1007/s12517-018-3809-7

[5] H. Hu, Y. Lu, C. Deng, B. Gan, Z. Xie, Y. Cai, and A. Chu, "Experimental study on grout–soil interaction effects in sandy soil under different water-to-cement ratios," *Buildings*, vol. 14, no. 4, p. 947, 2024. Available from: https://doi.org/10.3390/buildings14040947

[6] K. Lee, M. J. Cassidy, and M. F. Randolph, "Bearing capacity on sand overlying clay soils: experimental and finite-element investigation of potential punch-through failure," *Géotechnique*, vol. 63, no. 15, pp. 1271–1284, 2013. Available from: https://doi.org/10.1680/geot.12.P.175

[7] P. Patel and R. Sharma, "Finite element modeling of bearing capacity improvement in grouted sand foundations," *International Journal of Geotechnical Engineering*, vol. 15, no. 8, pp. 923–935, 2021.

[8] W. J. Long, X. Zhang, J. Xie, S. Kou, Q. Luo, J. Wei, *et al.*, "Recycling of waste cathode ray tube glass through fly ash-slag geopolymer mortar," *Construction and Building Materials*, vol. 322, p. 126454, 2022. Available from: https://doi.org/10.1016/j.conbuildmat.2022.126454