

Parametric study on the lateral deformation of the granular column using recycled materials

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Article

Keywords

Liquefaction
Granular column
Finite element method
Recycled materials
Effective stress
Lateral deformation

Abstract

This research article presents the results of lateral displacement behaviour of granular columns filled with stiff and flexible recycled materials reinforced in soft soil. In this investigation, finite element analysis was carried out to analyse the lateral displacement response with depth of granular column reinforced into soil stratum. Design parameters of granular columns have been varied including centre to centre spacing varied from 2 m to 4 m and the ratio of depth of columns to depth of soil stratum varied from 0.5 to 1.0. Homogenous soil stratum of 11 m square section has been analysed by varying lateral displacement with depth of columns and variation of principle effective stress with lateral displacement of granular columns. The outcomes reveal that with the increase in depth of granular column, lateral deformation decreases and principle effective stress increases. Similarly, lateral deformation increases for spacing to diameter ratio from 3 to 4 and for spacing to diameter ratio of 2, the zone of high concentrations has been observed due to disproportionate lateral interface among closely spaced columns, resulting in increased lateral deformation and compromised stability. These findings emphasize the critical importance of improving geometrical parameters in the design of granular columns incorporating recycled materials to enhance structural integrity and performance in geotechnical applications.

1. Introduction

Generally, in most countries, reduction in the settlement of infrastructure for long term and enabling economically design of foundation with adequate bearing capacity are prerequisites for infrastructure development. Excessive settlement from soft clay foundation could result in undrained soil failure in the absence of actual improvement in ground (Basack et al., 2018). Loss of shear strength in saturated soils as a result of excessive pore pressure generation associated with liquefaction leads to lateral displacement under seismic conditions. Many grounds improvement technique, such as compression, hardening, vertical drains, deep soil mixing and granular column (granular pile) might lessen the risk of liquefaction and the ensuing ground deformation (Lu et al., 2019). The vertical displacement with varying geometrical cases and consolidation effect has been shown in Pradhan & Tiwari (2024). Due to inadequate lateral confining pressures, granular columns were unable to support their load capacity in exceptionally weak soft clay, supplied from the nearby soils and might not even be sufficient to form the columns while they were being installed under a severe circumstance. Srijan & Gupta (2023) demonstrates by experiment that the soil stratum's bearing capacity rises with the use of vertical and horizontal reinforcement layers. Numerous academics

have examined the soil stratum and compatibility of granular columns thus far. Tan et al. (2021) simulated stone column integrity failure and high-risk locations during installation and injection, respectively, taking into account complex geological circumstances (interlayers). Remadna et al. (2020) demonstrates how accounting for the installation effect can lessen the deformation of the surrounding soil and the columns by raising the soil's lateral earth pressure coefficient. Rainfall induced slope failures have become more common in tropical regions due to increasing extreme rainfall events driven by climate change (Rangarajan et al., 2024).

Based on the previously mentioned research, it was evident from the ground model and all formalized approach stare the behavior of the granular columns in the composite soil was significantly analyzed. After examining the various studies mentioned above, it became evident that the behavior of granular columns in composite ground is extensively analyzed by field models and all analytical approaches. Despite the many benefits of using granular columns to prevent liquefaction, debris used as a filler material has a significant impact on the settlement profile. This analysis covered the granular column filler material that was the subject of several research. The appropriate use of stone aggregate derived from construction and industrial waste was taken into account in order to forecast the results. The present investigation employs parametric

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study across a broad range of parameters, revealing that the expected model effectively utilized to forecast the impacts of varying factors on the composite ground's settlement response and load carrying capacity. The degree of granular pile (GP) penetration into soil is included in the projected model. GP deformation moduli are mainly thought to be constant with depth. To forecast the expected site's settlement response, stratification of the soil layer is also taken into account. In this study, the reinforced soil model was designed to analyze the lateral displacement profile of the granular columns using finite element analysis. The group of nine granular columns varied geometrically with their centre to centre spacing (s) and depth of penetration of columns (L). The influence of principle effective stress (σ_1) varied with the lateral displacement (U_x) was also studied.

2. Materials

For numerical analysis, the primary material includes soft clay stratum and various recycled aggregates include marble, granite, sandstone, limestone, crushed brick, glass, and lightweight expanded clay aggregates (LECA) characterized by its own set of geotechnical properties such as modulus of elasticity and Poisson's ratio. These materials play a crucial role in accurately predicting the settlement of composite ground.

2.1 Soft clay

The soft clay considered for the analysis represents a natural weak soil layer that typically requires improvement. It

is characterized by low shear strength and high compressibility (CH). The properties assigned to soft clay includes $\gamma_{dry} = 16.63 \text{ kN/m}^3$. It was hypothesized that the E_s of soft clay followed a reverse relation with m_v for a specific pressure range (100-200 kPa). Table 1 shows the properties of considered soil.

2.2 Recycled materials

The granular column with grain size 10 mm to 20 mm was filled with substitute materials like broken brick, marble, granite, limestone, glass, sandstone, recycled concrete aggregate (RCA), and lightweight expanded clay aggregate (LECA). The excess of waste materials continues to be a problem for society because of the large amount of construction and demolition (C&D) waste stone aggregates, concrete, plastics and other materials that are produced each year all over the world. Table 2 shows the recycled material properties used in the analysis.

3. Numerical formulation

The Mohr-Coulomb failure criterion has been considered for soil behavior to evaluate displacement characteristics under given loading conditions. The linear elastic material model has been used for recycled materials signifies their relative stiffness. A general condition has been employed in which the homogenous soft clay was reinforced with a group of 9 granular columns. Filler aggregates between 10 mm to 20 mm were considered in recycled form including higher stiffness to lower stiffness. Higher stiffness materials

Table 1. Properties of soft soil.

Property	Range	Value	References
Elastic modulus, E_s (kPa)	3500-5600	5000	Ambily & Gandhi (2007)
Poisson's ratio (μ)	0.3-0.45	0.3	Yoo & Kim (2009)
Cohesion (c_u), (kPa)	3-5	4	Ambily & Gandhi (2007)
Angle of internal friction (Φ), Degree	18-22	20	Yoo & Kim (2009)
Dry Density (γ_{dry}), kN/m^3	12-16	13	Ambily & Gandhi (2007)

Table 2. Properties of recycled materials.

Materials	Elastic Modulus, (E_{gp}), (GPa)	Poisson ratio (μ)	References
Brick	10	0.25	Arulrajah et al. (2011)
Recycled concrete aggregates (RCA)	30	0.20	Gómez-Soberón (2002)
Lightweight expanded clay aggregate	4	0.16	Ardakani & Yazdani (2014)
Granite	50	0.20	Li et al. (2019)
Glass	25	0.25	Makishima & Mackenzie (1975)
Limestone	70	0.20	Christensen (1996)
Sandstone	35	0.20	Tian et al. (2016)
Marble	90	0.20	Christensen (1996)

($E_{gp} > 70$ GPa) include limestone, granite and marble, medium stiffness material ($45 < E_{gp} < 70$ GPa) include sandstone and recycled concrete aggregates (RCA) whereas lower stiffness material ($E_{gp} < 45$ GPa) include brick, glass and LECA. Figure 1 shows the mesh of the 3D model. Figure 2 shows the sectional shape of the ground condition considered for the analysis part having group of 9 granular columns with diameter (d) of the columns and the centre to centre spacing (s) has been varied as shown in the plan. Figure 3 shows the section of the granular columns with their length (L) reinforced into the soil deposit up to the stiff base (H_s). A soft clay stratum of 11 m square sectional shape has been analysed with finite element technique in PLAXIS 3D. The diameter (d) of the granular columns were kept constant during the analysis and assigned to 1 m where the depth (L) of the columns increased from 7.5 m to 15.0 m. For no slippage condition in the column and soil interaction, the hard stratum (H_s) was assumed at 15 m for the observation.

3.1 Boundary conditions

The boundary conditions employed for the analysis such that displacement was permitted at peripheral edges of the section of soil while radial displacement was constrained. Now, for the lowest section of reinforced soil, the displacement in radial and peripheral edges were not permitted.

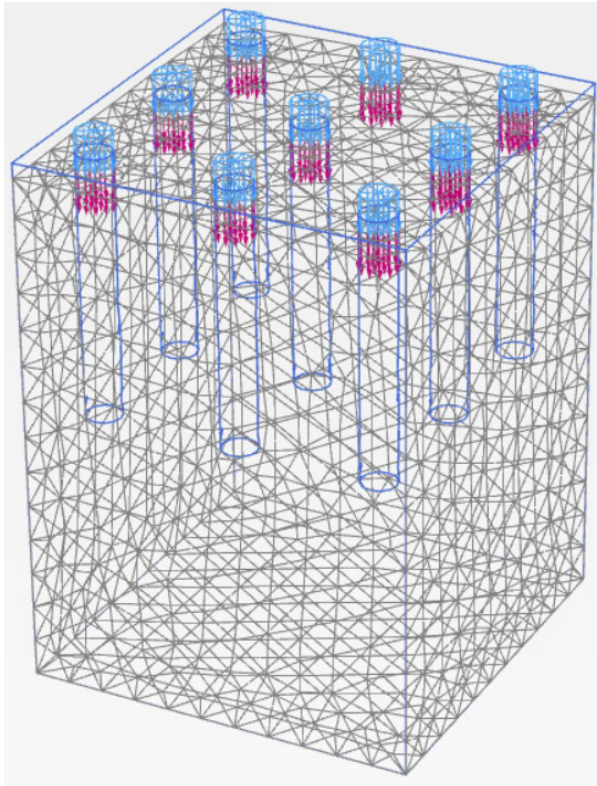


Figure 1. Mesh of the 3D model.

3.2 Parametric study

The geometry of granular columns varied in their spacing from 2 m to 4 m i.e., $s/d = 2$, $s/d = 3$ and 4. The diameter of 1 m has been assigned to the columns with variation in depth from 7.5 m to 15.0 m i.e., $L/H = 0.5$ to $L/H = 1.0$ up to hard stratum. A direct load of 100 kPa intensity has been applied to the columns in order to obtain the lateral displacement profile of the model. The lateral displacement (U_x) of the reinforced soil medium has been varied with spacing ($s/d = 2, 3$ and 4) and depth of columns ($L/H = 0.5$ to $L/H = 1.0$).

The model has been designed in the geotechnical software PLAXIS 3D which was used to simulate the model. For comparison of parametric values with lateral displacement of granular columns with different recycled materials, the analysis taken place of for wide range of parameters. The surcharge of 100 kN/m² has been applied to the granular columns with the prescribed displacement of 100 mm. Experiments are used to analyse the crucial mesh in order to accurately determine the corresponding designs. The situation where a uniform surcharge was applied to the granular columns and a soil layer was inserted at a suitable depth. Up to the hard layer, homogeneous ground conditions were taken into account. The

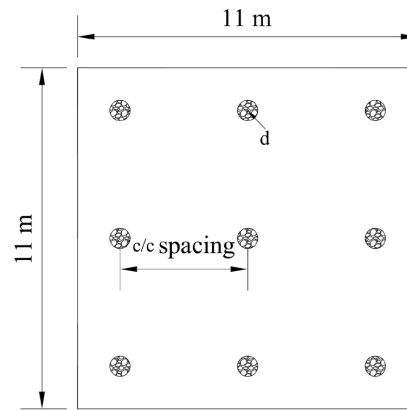


Figure 2. Plan of granular columns with soft soil.

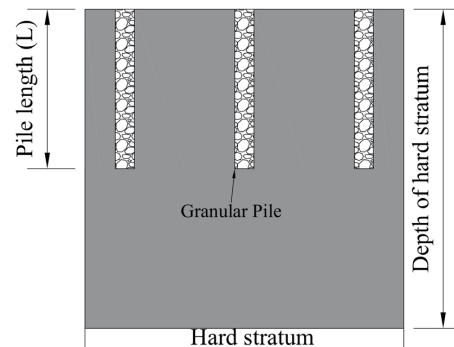


Figure 3. Section of soft soil reinforced with granular piles.

design study was predicted on the soil's (μ_s) and pile's (μ_{gp}) Poisson's ratios as well as their respective young's moduli (E_{gp} and E_s) and it was intended for the Poisson ratio to be constant up to the layer. Table 3 lists the granular pile (GP) parameters that were taken into consideration during design.

4. Result and discussion

4.1 Variation of lateral displacement of granular columns with depth ($L/H = 0.5$ to $L/H = 1.0$) for different values of spacing ($s/d = 2, 3$ and 4)

It was observed that with the increase in the depth of granular columns, the value of lateral displacement reduces to a certain extent. For $L/H = 0.5$, the maximum lateral displacement profile was observed between 0.5 m to 2.5 m while for $L/H = 1.0$, the maximum lateral displacement profile was observed between 7 m to 15 m. Similarly, the centre to centre spacing from 2 m to 4 m was assigned to the model to observe the variation of spacing with the lateral displacement. In the analysis, high stress zone was developed for 2 m and 3 m spaced granular columns which leads to increase in the lateral displacement profile for the closely spaced columns. The optimum spacing of granular columns depends upon the sectional shape of the soil stratum and here, more prominent results were observed for 4 m spacing i.e., $s/d = 4$. The marble, limestone and granite show maximum reduction due to higher elastic modules while lightweight expanded clay aggregate, glass and brick shows minimum reduction due to lower values of elastic modules in the lateral displacement profiles of granular columns. The sandstone and recycled concrete aggregate show preferable results to minimize the lateral displacement profile to a certain extent.

Figure 4 shows the variation of lateral displacement for $L/H = 0.5$ and $s/d = 2$ granular columns made with recycled aggregates. Here, at 1 m depth of granular columns, the maximum variation of lateral displacement was observed for all materials. The maximum and minimum lateral displacement was observed for light weight expanded clay aggregates and marble i.e., 1.44 mm and 1.00 mm respectively. For other materials including limestone, brick, sandstone, recycled concrete aggregates, glass and granite, the values of lateral displacements were 1.03, 1.22, 1.15, 1.16, 1.22 and 1.09 mm respectively. At the upper section of column groups, the variation of lateral displacement was maximum as compared to lower depths due to punching.

Table 3. Geometry assigns for granular piles.

Dimensions	Values	References
Pile diameter (d) mm	1000	Castelli & Maugeri (2002)
Pile length (L) m	7.5-15.0 m	Castelli & Maugeri (2002)
Spacing (s) m	2-4 m	Zhang & Zhang (2012)
Rigid Base depth (H_r) m	15 m	Basack et al. (2017)

Figure 5 shows variation of lateral displacement profile for $L/H = 1.0$ and $s/d = 2$. At 9 m depth, the maximum lateral displacement variation has been observed for all the materials. The maximum and minimum U_x were observed for LECA and marble i.e., 0.93 mm and 0.30 mm respectively. Similarly, for other materials including limestone, sandstone, granite, glass and brick, the U_x reported as 0.35, 0.49, 0.42, 0.62 and 0.84 mm respectively. Here, in the lower section of column

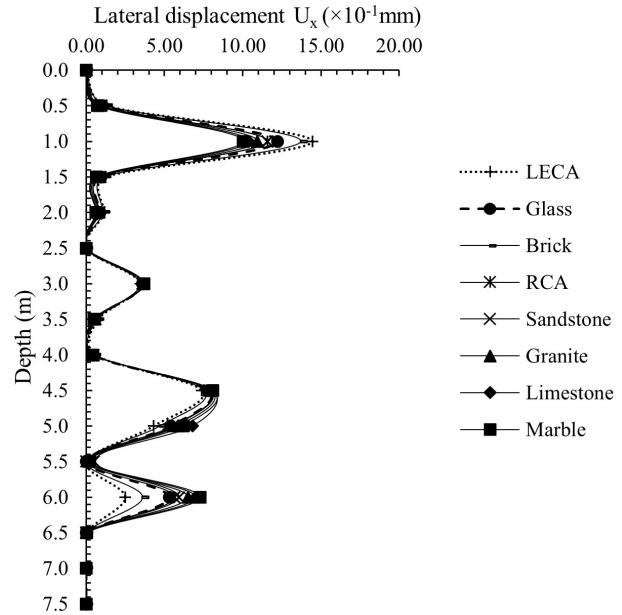


Figure 4. Variation of lateral displacement of piles with depth for $s/d = 2$ and $L/H = 0.5$.

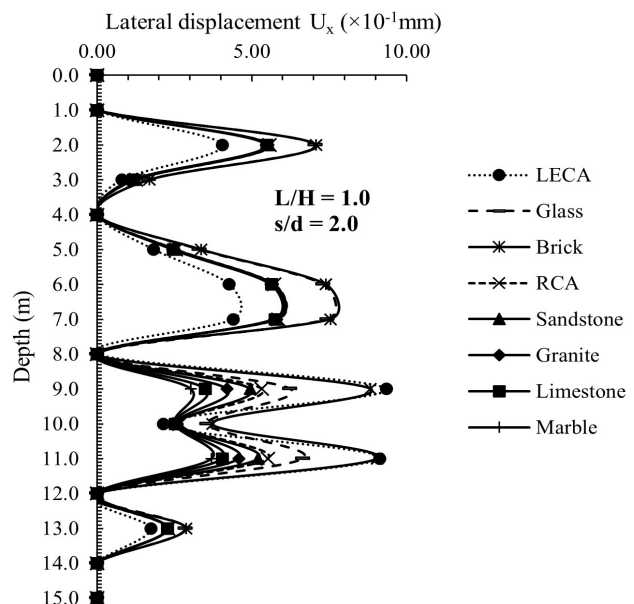


Figure 5. Variation of lateral displacement of piles with depth for $s/d = 2$ and $L/H = 1.0$.

groups, the variation of U_x profile was maximum compared to upper section. The increase in the concentration of stresses and generation of high stress zone at full depth of columns causes an increase in the peak of lateral displacement at lower section.

Figure 6 shows the variation of lateral displacement for $L/H = 0.5$ and $s/d = 3$ granular columns made with recycled aggregates. Here, at 0.5 m depth of granular columns, the maximum variation of lateral displacement was observed for all materials. The maximum and minimum lateral displacement was observed for light weight expanded clay aggregates and marble i.e., 0.8 mm and 0.23 mm respectively. For other materials including limestone, brick, sandstone, recycled concrete aggregates, glass and granite, the values of lateral displacements were 0.26, 0.67, 0.39, 0.42, 0.46 and 0.32 mm respectively. These outcomes show the influence of material stiffness, where marble, limestone and granite reduce U_x and other materials allow more deformation.

Figure 7 shows variation of lateral displacement profile for $L/H = 1.0$ and $s/d = 3$. At 9 m depth, the maximum lateral displacement variation has been observed for LECA and at 13 m depth, maximum lateral displacement variation observed for all other materials. The maximum and minimum U_x were observed for LECA and marble i.e., 0.62 mm and 0.27 mm respectively. Similarly, for other materials including limestone, sandstone, granite, glass and brick, the U_x reported as 0.53, 0.51, 0.52, 0.64 and 0.59 mm respectively. Here, the increase in depth of the column from 7.5 m to 15 m reduces the U_x to a certain extent. The values of U_x are highly influenced by material stiffness, spacing and depth of column, such that material with high value of modulus of elasticity shows

less U_x and with increased in the s/d ratio from 2 to 3, the confinement of surrounding materials get reduced, leading to increase in U_x in a particular interval.

Figure 8 shows the variation of lateral displacement for $L/H = 0.5$ and $s/d = 4$. Here, at 1 m depth of granular columns, the maximum variation of lateral displacement was observed for all materials. The maximum and minimum

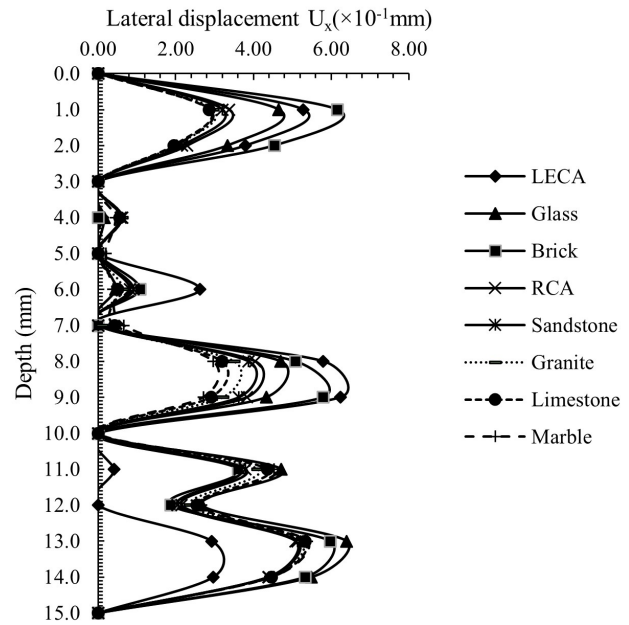


Figure 7. Variation of lateral displacement of piles with depth for $s/d = 3$ and $L/H = 1.0$.

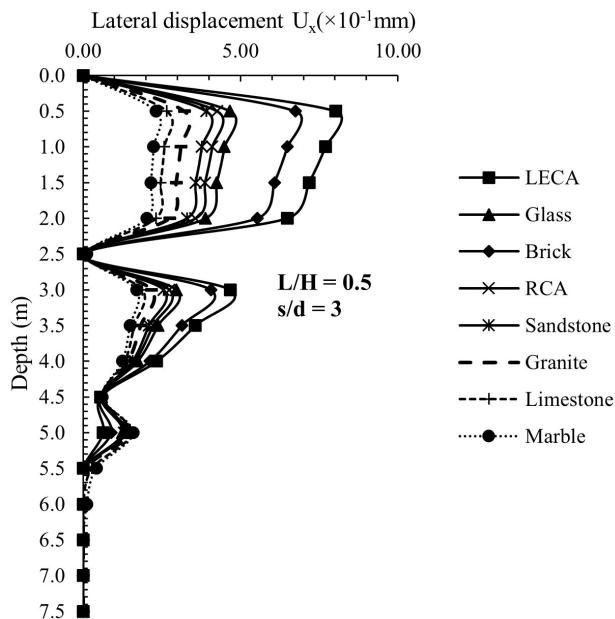


Figure 6. Variation of lateral displacement of piles with depth for $s/d = 3$ and $L/H = 0.5$.

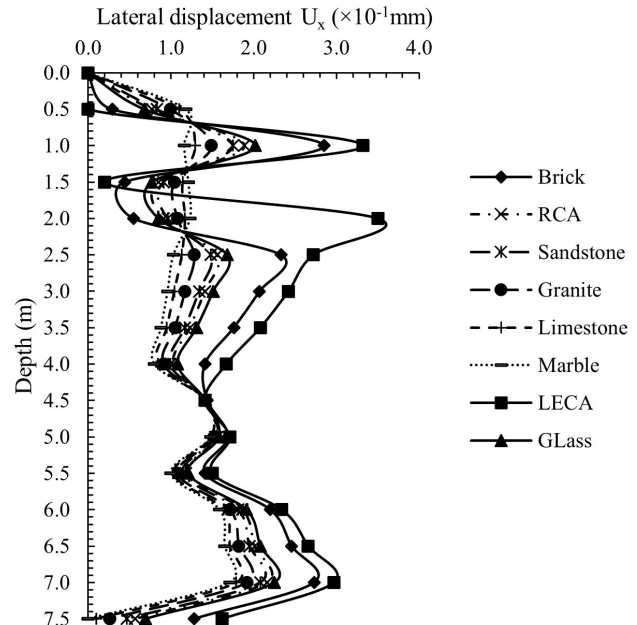


Figure 8. Variation of lateral displacement of piles with depth for $s/d = 4$ and $L/H = 0.5$.

lateral displacement was observed for light weight expanded clay aggregates and marble i.e., 0.33 mm and 0.12 mm respectively. For other materials including limestone, brick, sandstone, recycled concrete aggregates, glass and granite, the values of lateral displacements were 0.13, 0.29, 0.18, 0.19, 0.2 and 0.15 mm respectively. The depth of column group for 7.5 m engaging less with the deeper, stiffer soil layers, leading to more movement near the surface where the soil offers less confinement.

Figure 9 shows variation of lateral displacement profile for $L/H = 1.0$ and $s/d = 4$. At 5 m depth, the maximum lateral displacement variation has been observed for all the materials. The maximum and minimum U_x were observed for LECA and marble i.e., 0.69 mm and 0.6 mm respectively. Similarly, for other materials including limestone, sandstone, granite, glass, recycled concrete aggregate and brick, the U_x reported as 0.642, 0.669, 0.602, 0.68, 0.644 and 0.683 mm respectively. Here, with increase in the depth of column group, resistance from the surrounding materials increases which leads to larger accumulation of lateral displacement as varying stiffness of materials influencing the deformation.

4.2 Variation of principle effective stress with the lateral displacement for different recycled aggregates as filler in granular columns

Moreover, to examine the influence of relative stiffness of the materials, the principle effective stress of the columns was also varied with lateral displacement for all the materials with variation in the spacing, i.e., $s/d = 2, 3$ and 4. Here, with increase in the depth of penetration of columns in the soil, the

principle effective stress increases. The lateral displacement profile of the soil medium surges with the increase in the principle effective stress due to nonlinear behaviour of the soil. It was observed that nearby soil and granular columns undergo nonlinear stress-strain behaviour which results in the increment of lateral displacement with effective stress. The higher values of soil compression were also responsible for the increasement of the effective stress of the soil with increase in the lateral displacement of the soil.

Figure 10 shows variation of principle effective stress (σ'_1) with lateral displacement U_x for brick material. The spacing between the granular columns also varied from 2 to 4 m i.e., $s/d = 2, 3$ and 4. It was noted that with increase in the spacing between the columns, the lateral displacement U_x increases for $s/d = 2$ to $s/d = 4$. However, the results were similar for $s/d = 2$ and $s/d = 3$. The principle effective stress in brick material reaches up to 1350 kPa for lateral displacement of 76 mm corresponds to $s/d = 2$. For $s/d = 3$, the principle effective stress reaches up to 1162 kPa for U_x of 65 mm. Similarly, the principle effective stress for $s/d = 4$ reaches up to 871 kPa for lateral displacement of 141 mm. Due to high stress zone in the columns, the consideration of spacing was not showing significant results.

Figure 11 shows variation of principle effective stress (σ'_1) with lateral displacement U_x for recycled concrete aggregate (RCA). The spacing between the granular columns also varied from 2 to 4 m i.e., $s/d = 2, 3$ and 4. Here, the spacing $s/d = 3$ and $s/d = 4$ were more prominent than $s/d = 2$. The principle effective stress in recycled concrete aggregate reaches up to 1517 kPa for lateral displacement of 77 mm corresponds to $s/d = 2$. For $s/d = 3$, the principle effective stress reaches up to 1469 kPa for U_x of 69 mm. Similarly, the principle effective stress for $s/d = 4$ reaches up to 1253 kPa for lateral displacement of 124 mm.

Figure 12 shows variation of principle effective stress (σ'_1) with lateral displacement U_x for sandstone material. The

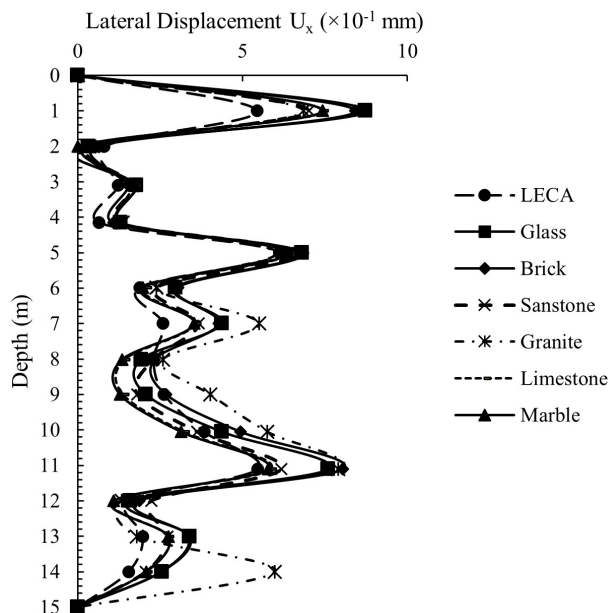


Figure 9. Variation of lateral displacement of piles with depth for $s/d = 4$ and $L/H = 1.0$.

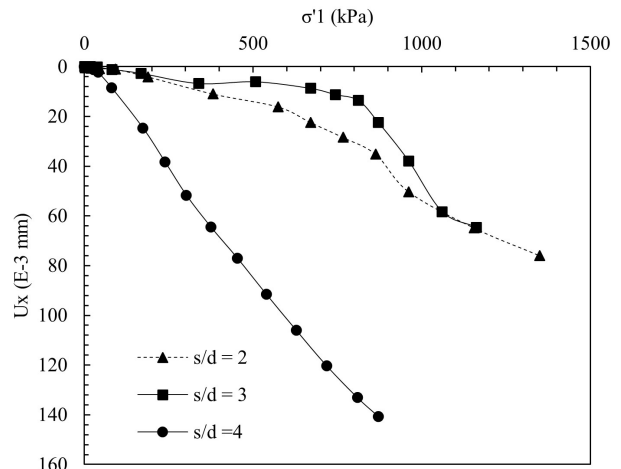


Figure 10. Variation of principle effective stress with lateral displacement for brick.

spacing between the granular columns also varied from 2 to 4 m i.e., $s/d = 2, 3$ and 4. It was noted that with increase in the spacing between the columns, the lateral displacement U_x increases for $s/d = 3$ to $s/d = 4$. The principle effective stress in sandstone material reaches up to 1900 kPa for lateral displacement of 77 mm corresponds to $s/d = 2$. For $s/d = 3$, the principle effective stress reaches up to 1723 kPa for U_x of 72 mm. Similarly, the principle effective stress for $s/d = 4$ reaches up to 1665 kPa for lateral displacement of 111 mm. Here also, due to nonlinear behaviour and high stress zone in the columns, the consideration of spacing was not showing significant results for $s/d = 2$.

Figure 13 shows variation of principle effective stress (σ_1) with lateral displacement U_x for granite material. The spacing between the granular columns varied from 2 to 4 m i.e., $s/d = 2, 3$ and 4. Similarly, here also the considerable results

were observed for $s/d = 3$ to $s/d = 4$. The principle effective stress in granite material reaches up to 2721 kPa for lateral displacement of 79 mm corresponds to $s/d = 2$. For $s/d = 3$, the principle effective stress reaches up to 2473 kPa for U_x of 77 mm. Similarly, the principle effective stress for $s/d = 4$ reaches up to 2577 kPa for lateral displacement of 83 mm.

Figure 14 shows variation of principle effective stress (σ_1) with lateral displacement U_x for limestone material. The spacing between the granular columns also varied from 2 to 4 m i.e., $s/d = 2, 3$ and 4. Here, almost similar results were observed for the spacing $s/d = 2, s/d = 3$ and $s/d = 4$. The principle effective stress in brick material reaches up to 3816 kPa for lateral displacement of 79 mm corresponds to $s/d = 2$. For $s/d = 3$, the principle effective stress reaches up to 3472 kPa for U_x of 82 mm. Similarly, the principle effective stress for $s/d = 4$ reaches up to 3627 kPa for lateral displacement of 62 mm.

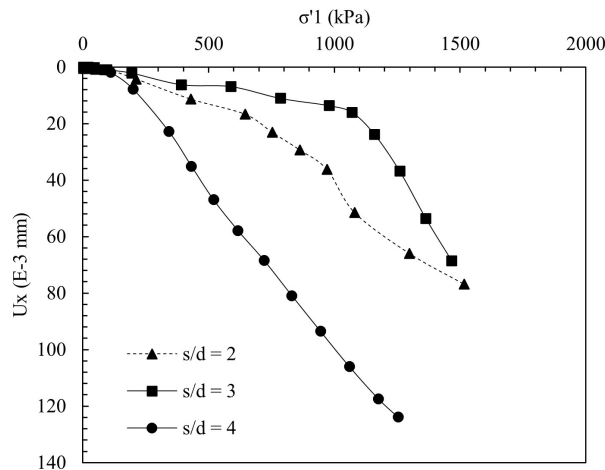


Figure 11. Variation of principle effective stress with lateral displacement for recycled concrete aggregate (RCA).

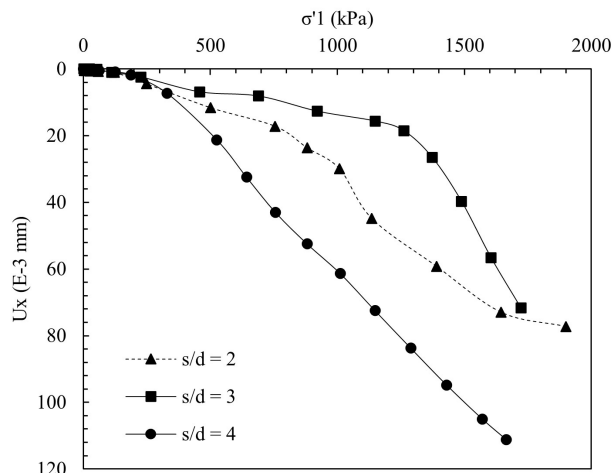


Figure 12. Variation of principle effective stress with lateral displacement for sandstone.

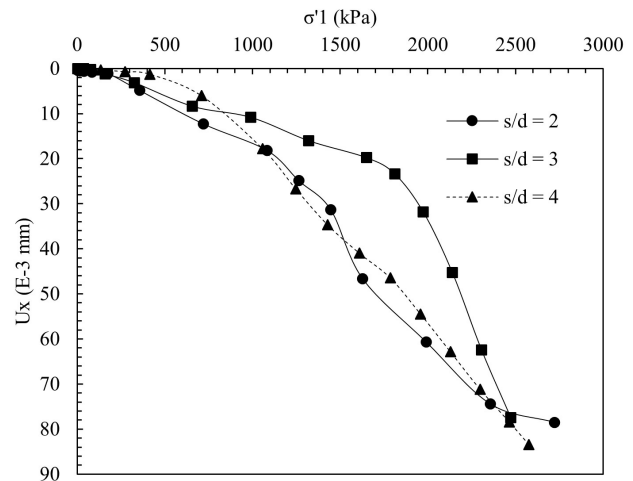


Figure 13. Variation of principle effective stress with lateral displacement for granite.

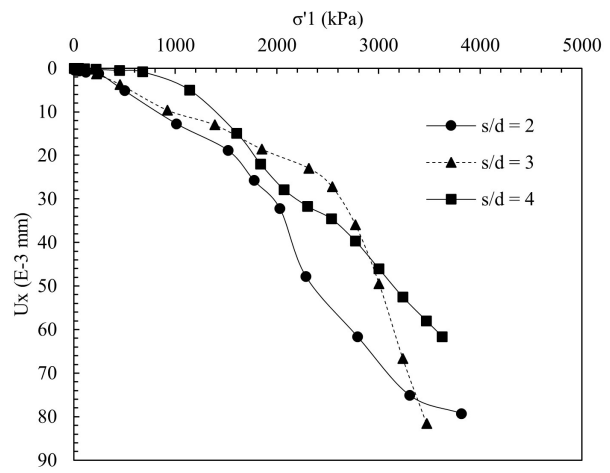


Figure 14. Variation of principle effective stress with lateral displacement for limestone.

5. Conclusion

A numerical investigation has been conducted using finite element techniques to evaluate the lateral deformation profile of the granular columns using stiff and flexible materials as a filler. Simultaneously, principle effective stress has been varied with lateral deformation in order to observe the behaviour of columns in terms of stress generation. The geometrical parameters were also varied with lateral deformation of granular columns including variation in spacing from 2 m to 4 m ($s/d=2$ to 4) and variation in depth of granular columns from 7.5 m to 1.0 m ($L/H = 0.5$ to 1.0). On the basis of the outcomes prevails; the following conclusion has been drawn:

- The marble has maximum resistance to the lateral displacement among all the materials due to its higher young modulus of elasticity whereas LECA has shown minimum resistance to lateral displacement;
- The marble, limestone, granite and sandstone showed satisfactory performance in granular column construction due to their higher stiffness making them suitable for enhancing the lateral stability in various geotechnical applications;
- With increase in the depth of granular columns in the soil stratum, the lateral deformation decreases and principle effective stress increases in significant amount;
- The principle effective stress increases with increase in the lateral deformation of granular columns. The peak of the lateral displacement increases with an increase in the spacing between the granular columns;
- At $s/d = 2$, the zone of high stress concentration has been generated causes increases in the lateral deformation;
- Similarly, the principle effective stress is minimum for brick and maximum for marble when varied with lateral deformation.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Bhaskar Pradhan: conceptualization, methodology, software, data curation, visualization, writing – original draft. Suresh Kumar Tiwari: supervision, validation, writing – review & editing.

Data availability

All data produced or examined in the course of the current study are included in this article.

Declaration of use of generative artificial intelligence

This work was prepared without the assistance of any generative artificial intelligence (GenAI) tools or services. All aspects of the manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

List of symbols and abbreviations

c/c	Center to center
c_u	Cohesion
d^u	Diameter of the pile
d_e	Unit cell diameter
r	Radial distance from z-axis /Coordinate of axis-symmetry
s	spacing
u	Displacement in r direction
w	Water absorption
w	Displacement in z direction
z	Axis of symmetry
E	Modulus of elasticity of granular pile
E_s^{gp}	Modulus of elasticity of soil
F_s^n	Load bearing capacity
$C\&D$	Construction and Demolition
CH	Clay of high compressibility
EC	Embodied Carbon
G	Specific gravity
GP	Granular Pile
H	Thickness of soil layer
L	Length of the pile
LECA	lightweight expanded clay aggregates
L_L	Liquid limit
OMC	Optimum moisture content
P_r	Perceive Settlement ratio
P_I	Plasticity Index
RCA	recycled concrete aggregate
U_x	Lateral displacement
UDL	Uniformly Distributed Load
γ_{bulk}	Bulk density
γ_{dry}	Dry density
μ_{gp}	Poisson's ratio of granular pile
μ_s	Poisson's ratio of soil
σ	Stress
σ_I	Principle effective stress
σ_{gp}	Stress in granular pile
σ_s	Stress in surrounded soil
σ_z	Intensity of uniformly distributed load
Φ	Angle of internal friction

References

- Ambily, A.P., & Gandhi, S.R. (2007). Behavior of stone columns based on experimental and FEM analysis. *Journal of Geotechnical and Geoenvironmental Engineering*, 133(4), 405-415. [http://doi.org/10.1061/\(ASCE\)1090-0241\(2007\)133:4\(405\)](http://doi.org/10.1061/(ASCE)1090-0241(2007)133:4(405)).
- Ardakani, A., & Yazdani, M. (2014). The relation between particle density and static elastic moduli of lightweight expanded clay aggregates. *Applied Clay Science*, 93-94, 28-34. <http://doi.org/10.1016/j.clay.2014.02.017>.
- Arulrajah, A., Piratheepan, J., Aatheesan, T., & Bo, M.W. (2011). Geotechnical properties of recycled crushed brick in pavement applications. *Journal of Materials in Civil Engineering*, 23(10), 1444-1452. [http://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000319](http://doi.org/10.1061/(ASCE)MT.1943-5533.0000319).
- Basack, S., Indraratna, B., Rujikiatkamjorn, C., & Siahaan, F. (2017). Modeling the stone column behavior in soft ground with special emphasis on lateral deformation. *Journal of Geotechnical and Geoenvironmental Engineering*, 143(6), 04017016. [http://doi.org/10.1061/\(ASCE\)GT.1943-5606.0001652](http://doi.org/10.1061/(ASCE)GT.1943-5606.0001652).
- Basack, S., Siahaan, F., Indraratna, B., & Rujikiatkamjorn, C. (2018). Stone column-stabilized soft-soil performance influenced by clogging and lateral deformation: laboratory and numerical evaluation. *International Journal of Geomechanics*, 18(6), 04018058. [http://doi.org/10.1061/\(ASCE\)GM.1943-5622.0001148](http://doi.org/10.1061/(ASCE)GM.1943-5622.0001148).
- Castelli, F., & Maugeri, M. (2002). Simplified nonlinear analysis for settlement prediction of pile groups. *Journal of Geotechnical and Geoenvironmental Engineering*, 128(1), 76-84. [http://doi.org/10.1061/\(ASCE\)1090-0241\(2002\)128:1\(76\)](http://doi.org/10.1061/(ASCE)1090-0241(2002)128:1(76)).
- Christensen, N.I. (1996). Poisson's ratio and crustal seismology. *Journal of Geophysical Research*, 101(B2), 3139-3156. <http://doi.org/10.1029/95JB03446>.
- Gómez-Soberón, J.M.V. (2002). Porosity of recycled concrete with substitution of recycled concrete aggregate: an experimental study. *Cement and Concrete Research*, 32(8), 1301-1311. [http://doi.org/10.1016/S0008-8846\(02\)00795-0](http://doi.org/10.1016/S0008-8846(02)00795-0).
- Li, X., Zhang, Z., Chen, W., Yin, T., & Li, X. (2019). Mode I and mode II granite fractures after distinct thermal shock treatments. *Journal of Materials in Civil Engineering*, 31(4), 06019001. [http://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002627](http://doi.org/10.1061/(ASCE)MT.1943-5533.0002627).
- Lu, J., Kamatchi, P., & Elgamal, A. (2019). Using stone columns to mitigate lateral deformation in uniform and stratified liquefiable soil strata. *International Journal of Geomechanics*, 19(5), 04019026. [http://doi.org/10.1061/\(ASCE\)GM.1943-5622.0001397](http://doi.org/10.1061/(ASCE)GM.1943-5622.0001397).
- Makishima, A., & Mackenzie, J.D. (1975). Calculation of bulk modulus, shear modulus and Poisson's ratio of glass. *Journal of Non-Crystalline Solids*, 17(2), 147-157. [http://doi.org/10.1016/0022-3093\(75\)90047-2](http://doi.org/10.1016/0022-3093(75)90047-2).
- Pradhan, B., & Tiwari, S.K. (2024). Granular pile settlement prediction on varying soil strata: FEM approach. *Transportation Infrastructure Geotechnology*, 11(6), 4161-4186. <http://doi.org/10.1007/s40515-024-00437-z>.
- Rangarajan, S., Rahardjo, H., Satyanaga, A., & Li, Y. (2024). Influence of 3D subsurface flow on slope stability for unsaturated soils. *Engineering Geology*, 339, 107665. <http://doi.org/10.1016/j.enggeo.2024.107665>.
- Remadna, A., Benmebarek, S., & Benmebarek, N. (2020). Numerical analyses of the optimum length for stone column reinforced foundation. *International Journal of Geosynthetics and Ground Engineering*, 6(3), 34. <http://doi.org/10.1007/s40891-020-00218-x>.
- Srijan, S., & Gupta, A.K. (2023). Vertically and horizontally reinforced end-bearing stone column: an experimental and numerical investigation. *Applied Sciences*, 13(19), 11016. <http://doi.org/10.3390/app131911016>.
- Tan, X., Feng, L., Hu, Z., & Zhao, M. (2021). Failure modes and ultimate bearing capacity of the isolated stone column in soft soil. *Bulletin of Engineering Geology and the Environment*, 80(3), 2629-2642. <http://doi.org/10.1007/s10064-020-02066-5>.
- Tian, H., Kempka, T., Yu, S., & Ziegler, M. (2016). Mechanical properties of sandstones exposed to high temperature. *Rock Mechanics and Rock Engineering*, 49(1), 321-327. <http://doi.org/10.1007/s00603-015-0724-z>.
- Yoo, C., & Kim, S.-B. (2009). Numerical modeling of geosynthetic-encased stone column-reinforced ground. *Geosynthetics International*, 16(3), 116-126. <http://doi.org/10.1680/gein.2009.16.3.116>.
- Zhang, Q., & Zhang, Z. (2012). A simplified nonlinear approach for single pile settlement analysis. *Canadian Geotechnical Journal*, 49(11), 1256-1266. <http://doi.org/10.1139/t11-110>.