Parametric Effect on Granular Columns: A Brief Review

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Abstract Granular columns are quite common in soft soils, mostly in clays, for improving pressure-settlement behavior of concern foundation. Load transmission in granular column mechanized by grain-to-grain contact and/or deriving resistance through interfacial interaction. Performance of such columns are highly depended on native soil condition which imparts passive pressure against the possible bulging in different configurations. Parameters, such as geometry (length and diameter), quality of in-filled aggregates, drainage condition, application of reinforcements etc., are responsible for the variations in performances. Phenomenon such as squeezing of soft clay into the aggregates and vice-versa reduces the functionality of granular column. Reinforcing the granular column with anchors, horizontal and 3-dimensional encapsulation has been very effective in enhancing the performance and/or reducing the detrimental effects. Studies have indicated the benefits and/or restrictions using granular columns under various parametric alterations. This paper presents a brief review on such parametric effects on granular columns under varying configurations and conditions.

Keywords Granular columns · Reinforcement · Parametric effects · Soft soil

1 Introduction

The granular inclusion in soft soil (as column) has been very effective in improving load bearing capacity and reducing excessive settlement of concern geo-structure. It is constructed by filling and compacting the granules, such as sand/gravel/coarse aggregates, by replacement (in a pre-bored column) or displacement (using vibration) technique. The granules, being stiffer, attracts majority of the imposed load and transfer deeper through contacts. Besides, being permeable, it allows faster pore water

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A. K. Dey et al. (eds.), *Proceedings of the 7th Indian Young Geotechnical Engineers Conference*, Lecture Notes in Civil Engineering 195,
https://doi.org/10.1007/978-981-16-6456-4_10

dissipation (acting as vertical drain) and speed-up the soil-consolidation; whereas, the surrounding soil provides lateral confinement (passive resistance) to reduce the bulging [1, 2]. In present days, artificially, additional confinement is provided by encasing the column with a suitable reinforcement, mostly with geosynthetics [3–6]. In such cases, the lateral restraint is applied in the form of hoop stress, generated through the encasement, during the bulge formation [7–10]. A number of study has investigated various parametric influences, such as geometry, in-fill density, encasement type etc., on the performance of granular columns. This article presents a brief review on such parametric dependencies of granular columns which would be useful for researchers and practicing engineers.

2 Parametric Studies

2.1 Physical Model Investigations

Physical model tests in varying configurations, with respect to geometry, type of loading, confining conditions and soil types etc., are performed to understand the behavior of granular columns. The effect of column-geometry (length, diameter etc.) was studied by Rao et al. [11]. The study indicated column length should be between 5 and 8 times the diameters of the column. Hughes and Withers [2], Hughes et al. [12] observed higher bearing capacity of granular column as compared to theoretical estimation. It was attributed to larger peripheral deformation (radial bulging) in field. Accordingly, different pattern of distortions (both vertical and lateral) of granular columns were also postulated under varying conditions. In connection to the above, Wood et al. [13] justified different modes of failure depending on arrangement of columns (in groups) and indicated that critical column length varies proportionally with the area ratio. Ambily and Gandhi [14] observed that the granular column performs better when subjected to a surcharge loading (i.e., load is shared by the surrounding soil) as compared to column loaded alone (Fig. 1a). It was found that the bulge formation is less in case of surcharge loading which is attributed to improved composite stiffness when soil was loaded simultaneously. At present, encasing the granular column (which provides an additional lateral resistance through hoop stress) has become very effective and popular in improving load bearing capacity and to limit the bulging. Malarvizhi and Ilamparuthi [7] have considered encased granular column and confirmed that bearing capacity improvement is proportional to the stiffness of the encasing material. However, the benefit has varied oppositely with increased column diameter. Such behavior was recognized as insufficient strain mobilization for required hoop stress generation. Ayadat and Hanna [4], Murugesan and Rajagopal [5], Ghazavi and Nazari [9] have also reported similar observations (as reduced vertical compression at the column-top) with stiffer encasement.

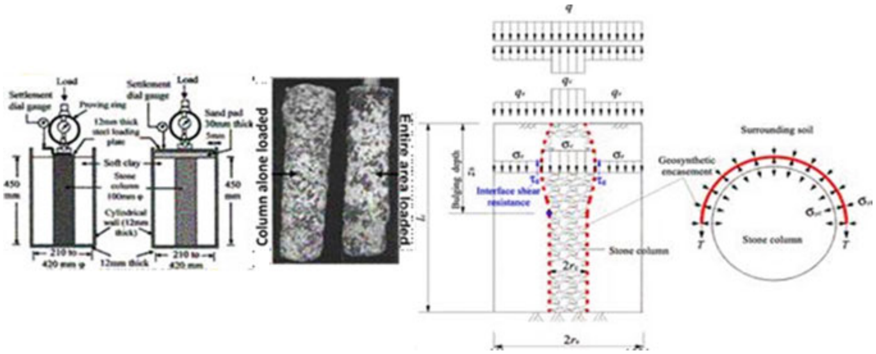

Fig. 1 **a** Influence of loading type [14]; **b** typical encasement mechanism [17]

2.2 *Theoretical Analysis*

Theoretical analysis is the contemporary of physical tests. In most of the cases, analytical and/or numerical solutions overcomes the difficulties/drawbacks of physical modeling (which involves several unavoidable uncertainties) and predicts an ideal behavior under varying configurations. Hughes and Withers [2] proposed an expression for ultimate stress generation on granular column. It is concluded that the bearing capacity of the column is notable up to a critical "length to diameter ratio". Continuing the study-type, Ambily and Gandhi [14] verified their physical test outcomes through Finite Element analysis and a design methodology is proposed considering "load sharing" between columns and the surrounding clay. Presently, software based simulative analysis of reinforced (encased) granular column is very popular. Murugesan and Rajagopal [8] studied the effective length (depth of maximum bulge formation) of encasement and concluded it as twice the column diameter. Added to the above, it is also mentioned that the stress intensity on the granular column increases with stiffer geosynthetics. However, Yoo and Kim [15], Yoo [16] observed no encasement-benefit beyond a critical stiffness which is independent of the area replacement ratio.

3 Mechanism of Granular Column

Primarily, installation of granular columns (as sand and/or stone column) are intended to carry the structural load. The load carrying capacity is developed through grain-to-grain stress propagation and mobilizing passive resistance by the surrounding clay. During loading, the aggregate dilates causing a lateral bulging. The bulging, to some extent, benefiting the granular system as anchor-column. In present practice, additional confinement is imposed through an encasement. It develops hoop stress and produces lateral support which can be increased with tensile-modulus of the encasing material. The “encasement” confines aggregates within and restricts the spreading. Thus, it creates “integrity” within the discrete aggregates and a better load transmission throughout the column length is established. In absence of encasement, the column material disperse into the surrounding clay (loss in aggregates) and vice-versa, creates problem in drainage and transferring the load. Regarding the loading pattern, a surcharge load on surrounding soil enhances the passive resistance which improves the stability of the column. The stress localization (which creates bulging) also gets reduced and improves the functionality of the column. Figure 1a depicts bulging of a stone column under different types of loading and the mechanism of encasement is presented in Fig. 1b.

4 Effecting Parameters

Studies have revealed various parameters effecting the performance of granular column. The following section briefly discusses the influencing parameters and their effect on the behavior of granular columns.

4.1 Undrained Shear Strength of Clay (c_u)

Undrained shear strength (c_u) of surrounding clay has significant contribution on the performance of granular column. It provides the initial lateral confinement to the granular column when encasement is not provided. However, in case of very low c_u, the clay and column-aggregates squeezed into each other causing disturbance in drainage and load carrying mechanism. Ambily and Gandhi [14] observed that the limiting axial stress on granular column is independent of c_u (Fig. 2a). The ground stiffness improves with surcharge loading which is independent of clay strength, however, depends on spacing between the columns (Fig. 2b). Najjar et al.

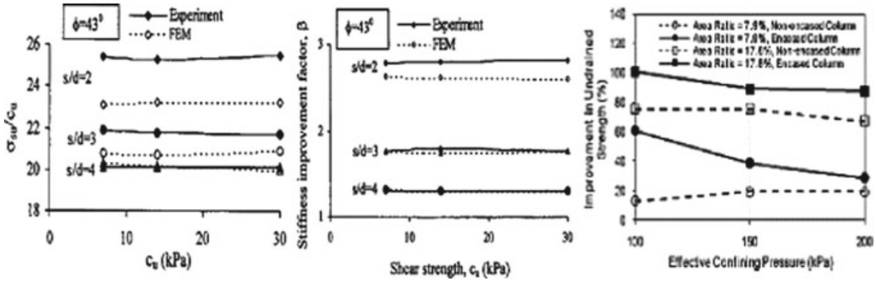

Fig. 2 Confinement effect of surrounding soil on **a** limiting axial stress of granular column, **b** stiffness [14], and **c** undrained shear strength of treated ground [18]

[18] observed the 'variation in shear strength with depth' is independent of the embedment depth of the sand column. However, for geotextile-encased column, the improvement in c_u decreased with the depth of confinement (Fig. 2c).

4.2 Internal Friction Angle of Aggregates (φ)

In general, the stiffness (thus the bearing capacity) of stone column increases with internal friction angle (φ) which depends on angularity, interface characteristics and packing of aggregates [19]. It was concluded that the gravel is the most efficient column material having high friction angle and requires lowest compactive effort for the desired degree of packing. Malarvizhi and Illamparuthi [7] observed that the influence of "φ" in "settlement reduction ratio" is more for unreinforced case (Fig. 3). This is due to stiffness of encasing material which provides additional confinement to loosely packed column material. Keykhosropur et al. [20] concluded that reduction in settlement and lateral bulging (due to greater friction angles in encased column) results in higher stability for the granular column (Fig. 4).

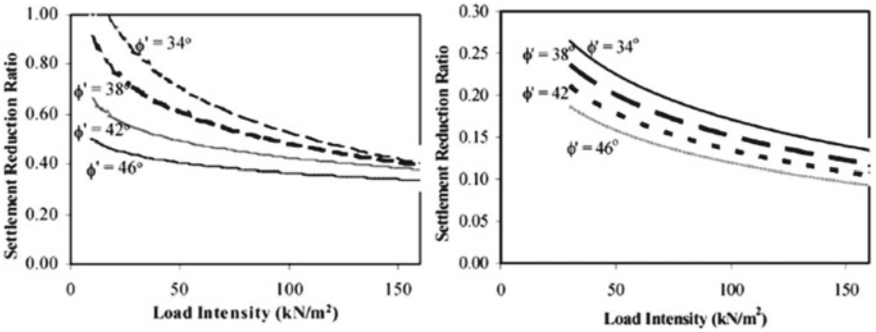

Fig. 3 Variation in settlement reduction ratio for **a** unreinforced and **b** encased column [7]

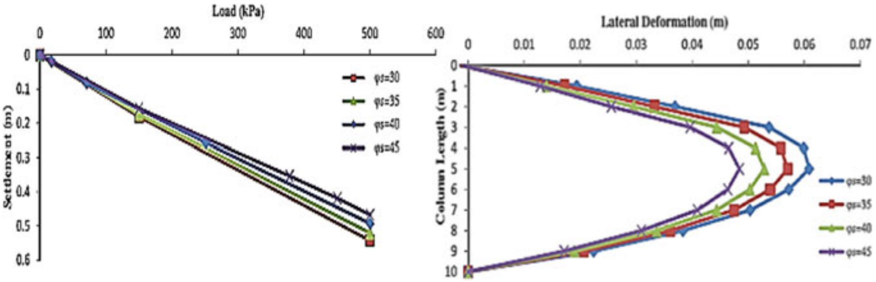

Fig. 4 Effect of φ values of encased granular column on **a** load-settlement response, **b** lateral deformation [20]

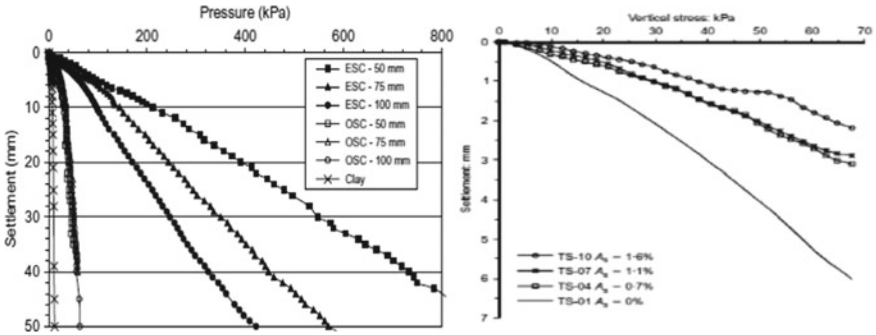

Fig. 5 **a** Load-settlement response of unreinforced and encased granular column for different diameters [21] and **b** effect of area ratio [25]

4.3 Diameter of Granular Column (D)

Method of installation and the stiffness of surrounding soil influences the most to the diameter of granular column. In practice, during installation/compaction, the diameter of granular column becomes larger depending on soil stiffness. This increase in diameter enhances the estimated bearing capacity and drainage function. Hughes et al. [12] obtained about 30% higher bearing capacity (in the field) as compared to the predicted values reported earlier [2]. Similar observation was also reported by Murugesan and Rajagopal [21]; in addition, they noticed a reduced rate of improvement for encased column due to limited hoop stress (Fig. 5).

4.4 Critical Length of Granular Column (l_{crit})

Performance of granular column depends on the critical length, l_{crit} (i.e., the length beyond which the granular column does not contribute). As per model tests the critical length to diameter ratio lies between 5 and 8 [2, 11, 13]. McKelvey et al. [22], Sivakumar et al. [23], Black et al. [24] reported that longer columns are useful for settlement control (due to adequate bulge formation); while, a punching failure can be expected for end-bearing shorter columns. Black et al. [24] observed larger deviator stress and lesser pore pressure generation at failure for a fully penetrating column triggering the aggregate-dilation during bulging. Ali et al. [6] noticed that end-bearing column performs better in load sharing irrespective of reinforcement condition.

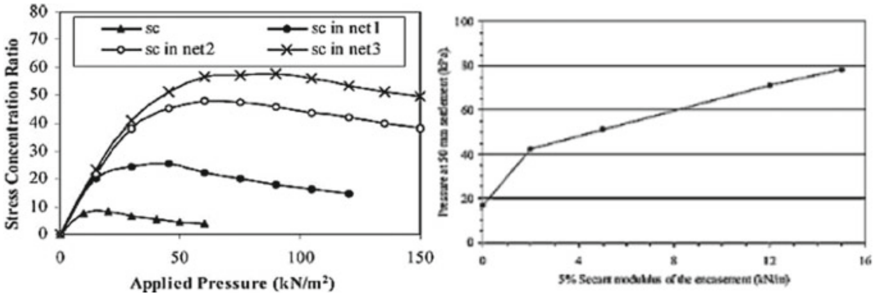

Fig. 6 **a** Stress concentration ratio of encased column [7] and **b** effect of modulus of encasement on the encased column [21]

4.5 *Modulus of Encasement (E_s)*

The stiffness of column is enhanced with stiffer encasement (Fig. 6) [7, 8, 15, 16]. Malarvizhi and Ilamparuthi [7] reported improvement in stress concentration ratio (SCR = Ratio of stress on column to that on adjacent soil) with stiffer encasement.

4.6 *Length of Encasement (l_{esc})*

The prime objective of encasement is to subdue the lateral deformation and provide confinement for imparting stiffness to the granular column. Murugesan and Rajagopal [21], Yoo and Lee [26] concluded the effective length of the encasement as 2–3 *D* from the top of the column. Ali et al. [6] recommended for the full length encasement, irrespective of end bearing or floating columns. However, Dash and Bora [27] observed that partially encased (60% of column length) floating column performs better which was attributed to "deep seated bulge formation" at the bottom.

5 Conclusions

This article present a brief review on the behavior of granular column under different parametric variations. Following conclusions may be drawn based on the discussions:

- The granular column can be floating or end bearing type.
- For short floating column, the failure occurs due to punching; while long column fails by bulging.
- Depth of maximum radial deformation (bulging) of a granular column is about of 2–3 times the column diameter from the top.

- The critical length to diameter ratio lies within 5–8, beyond which improvement is marginal.
- Performance increases with higher angle of internal friction of the aggregates.
- The stiffer is the encasement, higher will be the improvement (due to greater confinement generated with larger hoop stress mobilized).
- The effect of confinement decreases as the diameter of the encased granular column increases.

Acknowledgements The authors sincerely acknowledge the support received from DHESTBT, Govt. of West Bengal, India [Memo No. 183(Sanc.)/ST/P/S&T/6G-33/2017 dated 16/03/2018].

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