Stone Column Reinforcement of a Soft South African Clay: A Laboratory Investigation

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ABSTRACT: The current rate of development in the construction industry has given rise to higher demands for land. In pursuit of satisfying the needs of property developers, engineers have resorted to new ground improvement technologies to eventually implement construction on lands which were previously regarded as unfeasible or uneconomical for this purpose. This study therefore aimed at investigating the potential use of singular stone columns in improving a soft wet clay of South African origin. Bench scale tests were conducted to evaluate the effect of the moisture content of the base soil and the column diameter. The results indicated a clear improvement in the vertical applied stress as well as in the settlement of the clay, when subjected to a compressive load. These findings were ultimately used to generate information regarding the stress concentration ratio and the settlement reduction ratio.

KEYWORDS: Stone columns, Stress-settlement behavior, Stress concentration ratio, Settlement reduction ratio

1. INTRODUCTION

1.1 Background

The high rise in demand for developable land, in conjunction with the vast percentage of soft soils - estimated as 40 % by AGIS in 2011 - in South Africa, have rendered ground improvement techniques well sought after by many property developers and engineers. Stone columns, amongst the numerous techniques employed across the globe, possibly represent the most natural and ecologically neutral foundation system in existence. They are capable of serving the purpose of improving bearing capacity, reducing settlement, mitigating liquefaction or enhancing drainage of in-situ soil. Nevertheless, this technique which is often preferred in the Unites States, Europe and Asia (McKelvey et al., 2004; Isaac and Madhavan, 2009), remains barely discernible in the South African construction industry. The main reason for the limited use of stone columns can possibly be attributed to a lack of research, instrumented case studies and design specifications. In fact, it can be noted that the predominant techniques to be used for bearing capacity improvement and settlement minimisation are mostly dynamic compaction, dynamic replacement with dump rock and piling. However, often it can be remarked that stone column would have been a more appropriate method in terms of both cost and environmental reasons. Therefore, this study was undertaken to investigate the possibility of reinforcing a soft South African clay by crushed aggregate columns.

1.2 Stone column installation

Stone columns are in effect compacted granular columns which are installed in grounds of poor geotechnical properties with view of satisfying specific construction requirements for accommodating light structures such as low-rise housing, retail developments, industrial warehouses, waste treatment plants and car parks (Sivakumar et al., 2007). Simultaneously, the minimal removal of in-situ soils reduces the carbon footprint arising from fuel emissions during transportation as well as the cost associated with excavation and dumping. In general, these columns are installed by two mechanical methods namely vibration and ramming (Som and Das, 2006). In comparison with vibrated columns which use a vibratory probe to create an opening for granular fill placement by either the displacement or the replacement method, rammed columns are positioned by initially creating a pre-bored hole which is ultimately filled with a compacted material in multiple layers. The difference between the two approaches lies in the complexity of the installation. Vibrated columns require more sophisticated machines and skilled labour than rammed columns thereby making the technique more costly. Therefore, this study investigated rammed stone columns. Figure 1 shows the installation process of a typical rammed stone column.

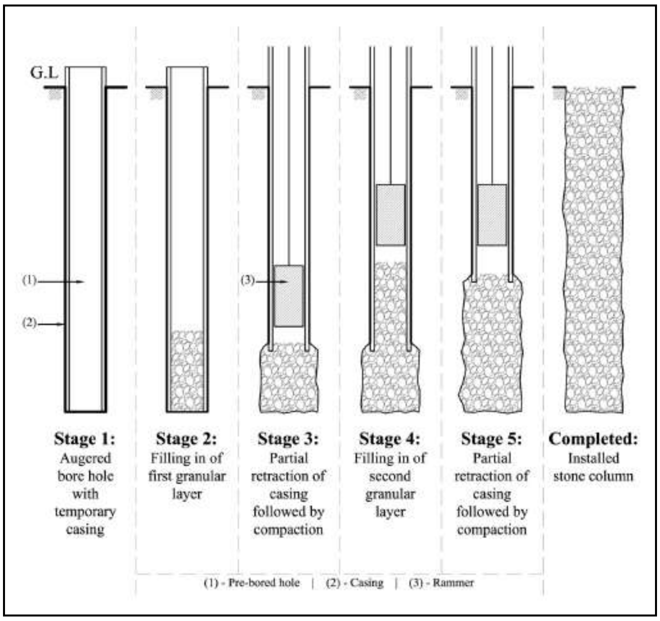

Figure 1 Installation of a pre-bored rammed stone column (Sobhee-Beetul, 2012)

1.3 A review of literature and study objectives

The technology of stone column is an old soil improvement approach dating back to the 1600s (VGNL, 2011). However, these granular columns were long forgotten until their rediscovery in the 1930s, as a by-product of vibroflotation. In early 1960s, the technique resurfaced as a very popular technique which came to be known as vibro-replacement or vibro-displacement (Hughes and Withers, 1974; Arman et al., 2009; Ambily and Gandhi, 2007).

Stone columns can be installed up to large depths and diameters. Purushottam Raj (2005) highlighted depths and diameters of up to 15 m and 750 mm respectively. These dimensions are generally dependent on the type of base soil, the type of column material, the moisture content of the in-situ soil, the column spacing and the degree of improvement required. In an attempt to understand the effect of each of these influences, many researchers have been in quest of experimental and theoretical solutions for estimating the performance of stone columns. The approach, to estimate the ultimate strength of a column within base soil, is the unit cell concept which is an idealization previously used by many researchers (Priebe, 1995; Goughnour, 1983; Abhijit and Das, 2000; Alamgir et al., 1996). Balaam et al. (1978) justified this analysis of a single column as being similar to investigating the behaviour of any column in a group of them. Ambily and Gandhi (2007) confirmed this statement through a series of tests conducted, whereby single column tests showed good comparison with group test results. On the other hand, Isaac and Madhavan (2009) conducted experiments on different types of materials which revealed stones and gravels as the strongest column materials.

The performance of a stone column is largely dependent on its diameter. Larger columns are prone to higher strengths which is attributed to the higher area replacement ratio. Partial replacement of the in-situ soft soil usually manifests into a denser ground which is further enhanced by an increase in the amount of the fill material. The relationship between the imported material and the in-situ soil extends to the effect of moisture content of the surrounding base soil. Since stone columns normally operates by the confinement pressure of the surrounding soil, it is evident that lower confining forces (arising from wetter grounds) will impact on the column strength. Consequently, the aim was to observe the performance of the reinforced soft clay under different conditions. More specifically, the effect of the column diameter and that of the moisture content on the following were investigated:

- stress-settlement behaviour of the improved clay,
- stress concentration ratio, and
- settlement reduction ratio.

2. EXPERIMENTATION

2.1 Materials

2.1.1 Cape Town clay (base material)

Excavated from a site in Green Point, Cape Town, this yellowish-brown clay of low plasticity was used to replicate a soft clay. The material was first oven dried and sieved through 0.6 mm sieves to remove the coarser fraction. Its liquid limit (LL) and plastic limit were determined as 34.7% and 21.8% respectively while the optimum moisture content (OMC) was 17%, corresponding to a maximum dry density of 1.80 Mg/m^3. Direct shear tests were conducted on the clay at OMC, LL and 1.2LL which resulted in friction angles of 39° for the driest sample and 0° for the wetter ones. A cohesion of 37 was reported at OMC while those at LL and 1.2LL were negligible.

2.1.2 Crushed aggregate (column material)

These greywacke hornfels aggregate were supplied by Afrisam, a company in Cape Town, South Africa. Their particles were angular in shape with sizes varying between 2.36 mm and 9.50 mm, and a mean grain size of 8.57 mm. The absence of fines, coupled with the shape and size of the particles, produced columns of large void ratios. In its loosest and densest states, this material had void ratios of 0.804 and 0.602 respectively. A sieve analysis yielded corresponding coefficients of uniformity and curvature as 1.25 and 0.97.

2.2 Test set-up and procedure

A bespoke rectangular wooden box of dimensions 1000 mm x 150 mm x 450 mm was used as the testing container. Steel braces were fixed along the longest sides of the box to provide support against the forces exerted by the base soil on the walls. To confirm the efficiency of the braces, LVDTs were placed on the sides of the box. Experiments were designed so that 3 moisture contents of the base soil (OMC, LL and 1.2LL) and 3 column diameters (D1=50 mm, D2=70 mm and D3=100 mm) were investigated. Extremely wet conditions (LL and 1.2LL) were studied to observe column performance under such circumstances, taking into account the low permeability of the fine grained base material. This observation is relevant for improvement of lands which are located in regions prone to high and persistent amount of rainfall. Besides, it was necessary to confirm the efficiency and feasibility of this technology in very wet grounds. The testing programme included a few control experiments whereby the base clay at each moisture content was not reinforced.

A wet sample was prepared at desired moisture content and stored for 24 hours in an airtight plastic container. The moist specimen was then placed into the box in layers of 50 mm until a bed thickness of 400 mm was obtained. Each layer was subjected to manual compaction through a 2 kg hammer dropping 12 times through 180 mm, to minimise the air void content. A greased open-ended steel cylinder (same as desired diameter of column) was carefully pushed down centrally in the clay bed until the base of the box was reached. The wet clay trapped within the cylinder was augered out using a hand cutter after which, the column material (crushed aggregate) was filled in compacted layers of 50 mm each until the surface of the clay bed was reached. For each layer, the cylinder containing the crushed aggregate was retracted by 40 mm which followed compaction of a similar degree to the base soil. Once the column was constructed, the surfaces of both the clay and column were levelled and the box was loaded on the Zwick Universal Compression and Tension Machine. A 35 mm thick rectangular plate, of width 147 mm and length twice the respective column diameter, was centrally positioned on the column which was then loaded via the Zwick machine at a speed of 1.2 mm/min. Tests were run until a settlement of 50 mm was achieved. This was based on a maximum allowable settlement suggested by Eurocode 7 for normal structures. Since the 50 mm settlement was achieved relatively fast, undrained conditions were favoured which eliminated the possibility of consolidation of the surrounding clay. In fact, after most experiments minimal heaving of the clay, in close proximity to the column, was noted. Experimental data was electronically captured and then analyzed to study the effect of moisture content of base soil and column diameter on the degree of improvement. Figure 2 shows a typical experiment column set-up.

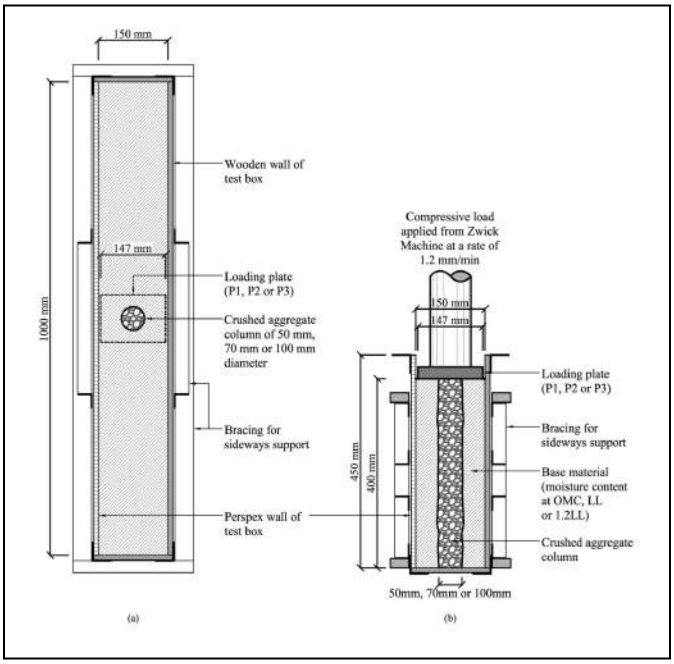

Figure 2 Column arrangement in the test box
(a) Plan of column in box, (b) Section of test box

3. RESULTS AND ANALYSIS

3.1 Stress-settlement relationship

The stress-settlement results are presented in Figures 3 and 4 to facilitate understanding of the effect of column diameter and moisture content of the base soil. Each graph shows control experiment results, alongside improved clay ones, to facilitate understanding of the degree of improvement achieved with column inclusion under similar conditions, the following notations have been used to denote each of these factors: M1=OMC, M2=LL and M3=1.2LL; D1, D2 and D3 are column diameters of 50 mm, 70 mm and 100 mm respectively; P1, P2 and P3 are the corresponding loading plates of respective length 2D1, 2D2 and 2D3.

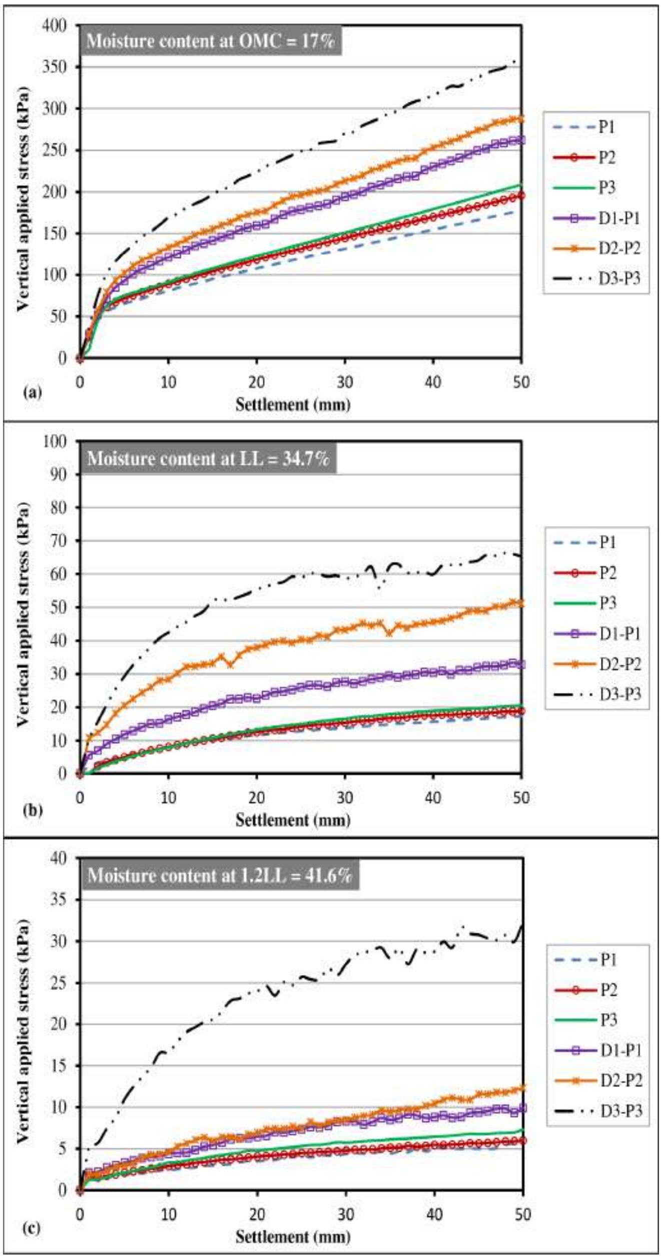

Figure 3 Effect of column diameter on stress-settlement behaviour at base clay of moisture content (a) OMC, (b) LL and (c) 1.2LL

Generally, the inclusion of reinforcing columns produced an increase in the vertical applied stress, with a simultaneous decrease in settlement. It was further observed that the larger the diameter, the higher the vertical applied stress accommodated by the column. In fact, an increase of 100 kPa was even noted when the column diameter was doubled at OMC. At higher moisture contents of LL and 1.2LL, the difference in vertical applied stress was even more dramatic, with the 100 mm diameter column having about 3 times the stress capacity of the 50 mm column in base clay at 1.2LL. This observation was indicative of the degree of improvement provided by large stone columns at high moisture contents although the magnitude of the applied stress decreases drastically. This sharp decrease was mainly due to the lower confining pressures provided by the surrounding wet clay. Since stone column performance was dependent on these confining forces, their efficiency was largely reduced. A further observation in the trends of the graph was the occasional 'saw-toothed behaviour' of the curves. This phenomenon was mainly a reason of the repeated process of build up and subsequent collapse of resistance forces which occur between the aggregates during sustained loading.

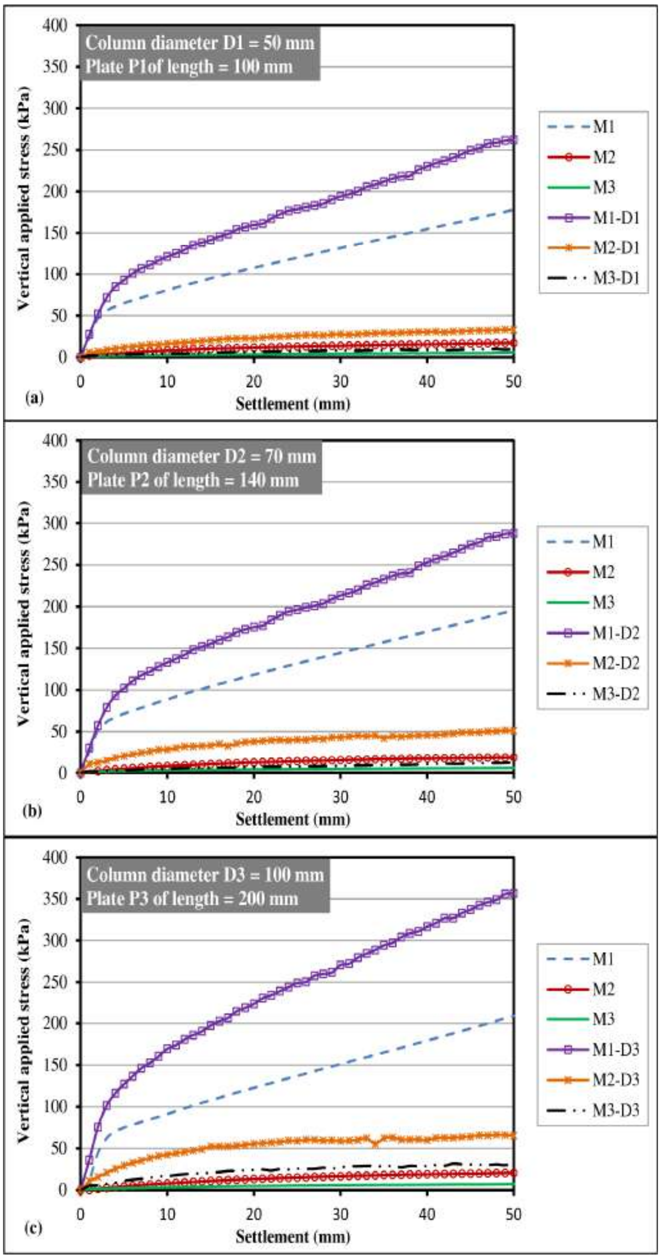

Figure 4 Effect of moisture content of the base soil on stress-settlement behaviour at column diameter (a) 50 mm, (b) 70 mm and (c) 100 mm

3.2 Stress concentration ratio, (n)

In this study, the stress concentration ratio (n) was defined as the ratio of the stress of the composite ground to that of unimproved. Since the numerator in this ratio is expected to be greater than its denominator due to the effect of reinforcement, higher values of n indicate better improvement. Figures 5(a) and 5(b) present the effect of column diameter and moisture content of the base clay on n respectively.

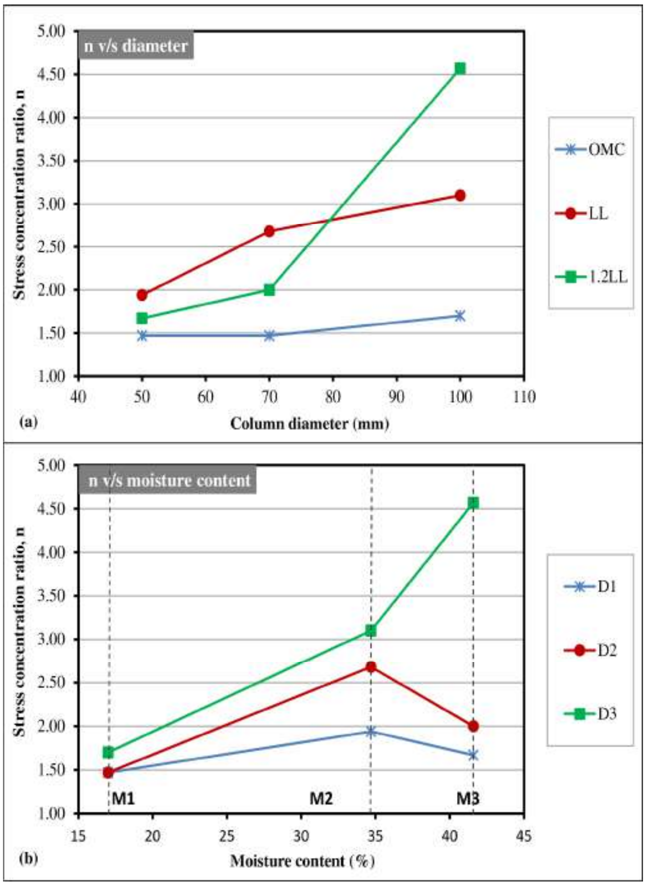

Figure 5 Influence on stress concentration ratio from the variation of (a) column diameter, (b) moisture content of the base clay (After Sobhee-Beetul, 2012)

In general, an increase in column diameter results in higher n-values irrespective of the moisture content of the base clay. This trend is influenced by the amount of replacement material occupying the test specimen. Crushed aggregate particles, being coarse, large and strong, produce stiff columns having high vertical bearing stresses. Hence, n rises with an increase in column stiffness which results from column enlargement. At OMC, the change in n is almost negligible. However, at higher moisture contents (LL and 1.2LL), the percentage improvement accelerates with an increase in moisture content. Approximately 60% improvement, increase in n from 1.94 to 3.10, is recorded when a column of 50 mm doubles its size at LL. The range of n-values generated through this research shows good agreement with Barksdale and Bachus (1983) who specified typical n values ranging between 2.5 and 5.

With an augmentation in the moisture content of the base clay to 1.2LL, the degree of improvement obtained in n demonstrates a steep increase. In fact, the n-value for a 100 mm column was about 3 times that of a 50 mm column. Interestingly, as the column diameter gets larger in highly wet clays, the improvement is generally sharp. This behaviour can be explained by the low confining stress field generated by very wet soils. The large angular aggregates on the edge of the column generally intrude the soft clay, rendering a contaminated column surface. Consequently, the frictional strength of the aggregates decreases which negatively impacts on the stress capacity of the column (McKenna et al., 1975). However, with larger columns, the larger amounts of replacement material compensate for this loss in strength and thus produce a better improved ground.

3.3 Settlement reduction ratio, (SRR)

Settlement reduction ratio is herein described as the ratio of settlement in improved ground to that in unimproved ground, for the vertical applied stress corresponding to a settlement of 50 mm for the respective control tests. In comparison with n, where larger ratios indicate better improvement, SRR is preferred to be low since it indicates less settlement. Figures 6(a) and 6(b) describe the SRR-diameter and SRR-moisture content relationships respectively.

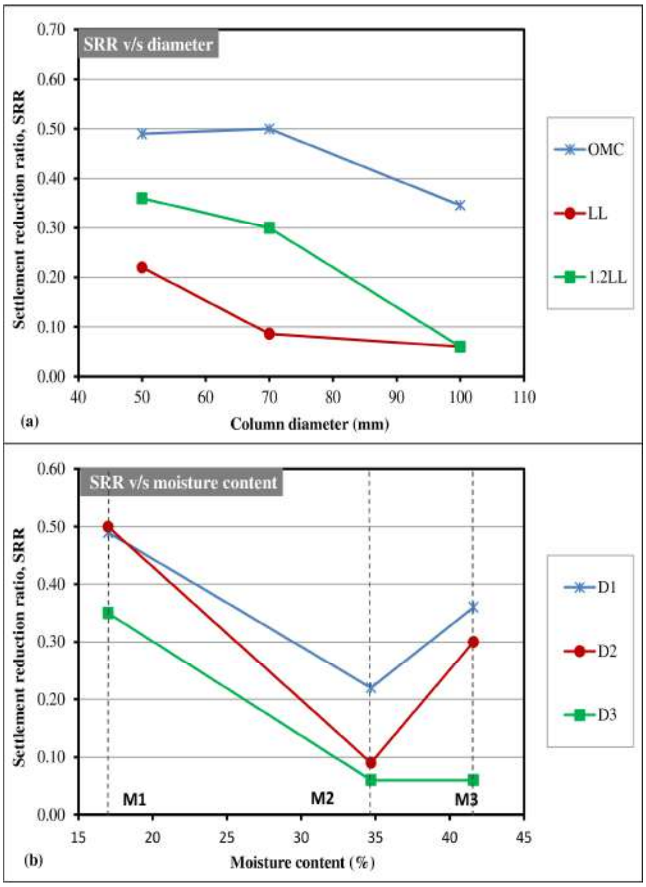

Figure 6 Influence on settlement reduction ration from the variation of (a) column diameter, (b) moisture content of the base clay (After Sobhee-Beetul, 2012)

The relationships obtained shows a general decrease in SRR as the columns were enlarged. However, the difference in SRR between 50 mm and 70 mm columns is minimal compared to that between the smallest and the largest columns. This observation again relates to the amount of strong replacement material producing stiffer columns.

At OMC, SRR reduction was relatively low. Nevertheless, further wetting of the base clay to LL and 1.2LL demonstrates a drastic reduction in SRR. In fact, the SRR value diminishes by at least 50% when the 50 mm column doubles its diameter. Although settlement reduction is best noted in base clays of higher moisture contents, the sharp improvement holds true only up to a moisture content of LL. Beyond this point, the SRR-value is again increased as a result of the low confining stresses which encourages partial horizontal movement of some crushed aggregates into the clay bed.

The SRR of large columns at these moisture contents normalizes to a constant value of 0.06. In this study, SRR ranged between 0.05 and 0.065 which is an observation in line with Zahmatkesh and Choobbasti (2010).

4. APPLICATIONS

Stone columns can generally be used as ground improvement for poor soils subjected to lightweight structures. Although these columns can be installed either floating or touching the hard stratum, this study ensured that all columns were installed up to full depth of the test box, thus depicting a field scenario of a stone column extending to the hard stratum. This type of installation eliminates the possibilities of columns punching through the soil. As such differential settlement is drastically minimised. Generally, the tested columns showed only bulging behaviour which was predominantly in the upper third of the column; clearly indicating their adequate carrying capacity. Based on the common local applications requiring enhancement of the ground conditions for construction purposes, rammed stone columns can potentially be used to support light weights in the following circumstances: strip footings, houses (maximum of two storeys), embankment support, storage tanks such as oil tanks, and slope stability. The technique would be of utmost interest in water logged soft soils, due to the high permeability of crushed aggregates which encourage faster drainage.

5. CONCLUSION

This study attempted to reinforce a South African clay with stone columns in a laboratory testing tank with a view of verifying the effectiveness of this technique locally. The technology was proposed for South Africa since it is a cost effective, easy and environmentally friendly ground improvement approach which is barely used in the country, where the local soil coverage constitutes roughly 40% of weak soils. A local field clay was used as the base material while columns were produced from crushed aggregates. The aim of the study was to improve the vertical applied stress of the base clay while simultaneously reducing settlement. As such, column diameter and moisture content of the base material was varied to understand their effect on the degree of improvement. The results obtained revealed significant improvement in both vertical applied stress and settlement. The stress-settlement relationships generated were ultimately analysed in terms of stress concentration ratio, n, and settlement reduction ratio, SRR. Based on the analysis, the following main conclusions were drawn:

- Singular column inclusion showed considerable improvement in both vertical applied stress and settlement of the South African clay.
- Irrespective of the moisture content of the base soil, the vertical applied stress generally increased with an enlargement of columns. As such, the stress concentration ratio also increased. For this study, n varied between 1.50 and 4.50.
- In the wettest clay, the 100 mm diameter column produced a vertical applied stress of approximately 5 times that of the unimproved clay, at a settlement of 50 mm.
- The stress concentration ratio of the 100 mm column increased as the base soil was made wetter.
- A reduction in SRR was noted as the moisture content was raised to LL, beyond which the settlement reduction ratio increased yet again. The SRR for this study varied between 0.05 and 0.65.

Further research is proposed to investigate the behaviour of these columns in soils of varying conditions of saturation. Additionally, to validate the findings, pilot scale tests must be considered too.

6. ACKNOWLEDGEMENTS

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