

Evaluating an Improvement in Settlement Using Recycled Concrete Aggregate as Stone Column Filler Material

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Abstract— Growing human population and its conterminous effect on infrastructure development has led to challenges with the availability of soil with good bearing capacity and strong settlement resistance to support these built structures. These challenges have often been addressed by installing pile foundations to secure the structure to a more stable bedrock beneath the weak soil or by replacing the weak soil with one having more potent geotechnical properties. However, these solutions are expensive and time-consuming, especially for low structural loads. Many studies have therefore been conducted to explore techniques for improving in-situ soil properties to avoid the significant cost that will be incurred. Stone columns are mostly used due to their adaptability in improving the bearing capacity and reducing differential settlement in various soils. The sourcing of aggregates for stone columns from quarry sites is an unsustainable approach due to the potential depletion of the natural resource. Innovative and environmentally friendly means of using alternative materials like construction waste have thus been explored. This study focused on using numerical methods to evaluate an improvement in settlement of clayey sandy gravel of South-Central Leeds using recycled concrete aggregate as filler material for stone columns. Analysis of the settlement characteristics of this soil was performed on Settle3 software. From the analysis, total consolidation was reduced by up to 19 % when the sample was reinforced with stone columns made of recycled concrete aggregate. So did an improvement in differential settlement.

Index Terms— settlement, stone column, recycled concrete aggregate, sustainability, ground improvement.

I. INTRODUCTION

With the rapid increase in human population, land availability for infrastructure is on the decline, leading to sites with poor soil being available for the development of any civil engineering structure. This phenomenon has made sites with weak soil deposits like soft clayey soils and mixtures of soft-firm cohesive/loose-medium dense non-cohesive soils (gravelly silty sand/ clayey sandy gravel), available for use in the construction industry [1]. With the characteristic challenge of low shear strength and high compressibility, these weak soils can only bear their self-weight, and thus, any additional load would cause great deformation. [2].

With the Civil engineering industry increasingly being confronted with the challenge of sites with these poor soils, driving piles deep beneath these soils to be secured on a strong formation or increasing the area of foundation can both be an expensive and time-consuming solution. Replacing these weak soils with soils with good bearing capacity and settlement also seems only economical if it involves small quantities and depth of soil. An alternative measure is thus to improve the ground to a desired depth using various techniques by modifying its physical properties to achieve appropriate geotechnical performance for an effective and economical construction [3].

Vibro Stone columns, one of the well-known methods of improving the soil, involves the replacement of soft soil with compacted columns of granular material. Stone column is the most commonly used ground improvement technique in the United Kingdom (UK), with application dating back to the late 1950s and early 1960s [4]. Its introduction was in response to challenges with unsuspected cohesive and non-compactible soils in projects abroad. Stone columns have since been applied to improve a range of soils, including made ground and weak fine-grained soils, where 75 % of all stone column applications in the UK are towards stabilizing made grounds [4].

This results in the composite material (soil and stone column) having high shear strength and low compressibility [5]. The filler material for stone columns is generally naturally extracted aggregates, which with over-exploitation, could result in the depletion of the natural resource.

Hence, evaluating an improvement in settlement of loose-medium dense cohesive soils using recycled concrete debris, which may have just landed in landfills and using them as filler material in stone columns, is both an advancement in geotechnical technology and environmental sustainability. It will help achieve the sustainability aspirations of the UK construction industry.

The use of recycled concrete aggregate from demolition waste has reflected an overall increase in the performance of the geotechnical properties [6]. The grain sizes of recycled concrete are like stones used for stone columns [5]. It is, therefore, necessary to explore and expand the research of using recycled concrete aggregate as filler material for stone columns, as this study seeks to achieve.

II. MATERIALS AND METHODS

A quantitative/ numerical analysis using finite element methods provides a more detailed set of results; it is a relatively fast and less expensive approach. For these reasons, this method, together with a qualitative review of relevant literature (case studies) were employed in analysing an improvement in the performance of clayey sandy gravel using recycled concrete aggregate as stone column filler material.

Settle3, a three-dimensional software developed by Rocscience that gives a 3D interface of results yielding from soil profiles and loading conditions, was used for the analysis. Settle3 gives an understanding of vertical settlement and consolidation of soil under various surface load orientations such as foundations, embankments and shallow excavations [7]. Additional calculation of the

carbon footprint of the process was conducted to ascertain the environmental benefits of using recycled concrete aggregate as stone column filler material.

Design and Modelling

A digital model of the head deposit with alluvium made of clayey sandy gravel with a saturated unit weight of 20kN/m³ from South-Central Leeds was created on Settle3 software. The model had a homogeneous thickness of twenty meters, additional soil parameters are in Table 1 below. This model was subjected to an embankment loading stress of 80 kPa from a hypothetical problem of embankment loading by [8] in their work on suggesting a simplified homogenous method for stone column designs. The embankment load was layered in three stages, from an unloaded layer to the first load to the second and final layer of loading. This was done to ascertain variations in the soft soil’s behaviour at each stage of loading.

The model precluded the 1-metre crust above the soil from the case study. The slope gradient of the embankment followed a 1:2 slope gradient of vertical to horizontal (V:H). Detailed geometry and geotechnical properties of the embankment are in Table 2. Settlement analyses on the modelled soft soil layer were then performed. The soil was then reinforced with square patterned stone columns made of recycled concrete aggregates with properties harnessed from Coatbridge, Scotland, as indicated in the study of the use of recycled aggregates in stone columns [9].

Parametric Study

As stated earlier, this is a case study of South-Central Leeds, and thus, all soil parameters summarized in Table 1 below are from the region. The parameters highlighted below were used, with average values found for bulk and dry density, while upper or lower limits were selected for others.

Table 1: Geotechnical Parameters of South-Central Leeds Head Deposits [10]

Moisture Content (%)		Liquid Limit (%)		Plastic Limit (%)		Bulk Density (Mg/m ³)		Dry Density (Mg/m ³)		Mv Class		Shear Strength (Cu)		Angle of Friction Φ (degrees)	
17	164	33	61	20	65	2.08	121	1.57	13	3	6	55	130	5	130
14	22	28	39	17	22	1.98	2.14	1.53	1.67	3	3	36	84	0	14
12	28	24	44	15	27	1.86	2.20					116.5	20	0	20
10	43					1.78	2.26					9	175	0	28

Computations

The three most important parametric factors in computing settlement of stone columns are the area replacement ratio, the stress concentration ratio and loading intensity [8]. The stress reduction approach will be employed for the settlement calculation.

Area Replacement Ratio

Equation 1 for the area replacement ratio (a_s) is defined as the ratio of the cross-sectional area of a column to the influence area of the column [11]:

$$a_s = \frac{A_c}{A_e} = C \left(\frac{d_c}{s}\right)^2 \tag{1}$$

where, a_s = area replacement ratio

A_c = cross-sectional area of the column

A_e = tributary area of the column or influence area of the column

d_c = diameter of the column = 1 meter

s = center-to-center spacing between columns in a square of equilateral triangular pattern = 2 meters

C = constant ($\frac{\pi}{4}$ or 0.785 for a square pattern or $\frac{\pi}{2\sqrt{3}}$ or 0.907 for an equilateral triangular pattern)

The area replacement ratio (a_s) is therefore = $(0.785)\left(\frac{1}{2}\right)^2 = 0.2$

Stress Concentration Ratio

Equation 2 for the stress concentration ratio is given as [11]:

$$n = 1 + 0.217 \left(\frac{E_c}{E_s} - 1\right) \tag{2}$$

Where, E_s = elastic modulus of the soil = 5000kPa

E_c = elastic modulus of the column = 45000kPa

According to (Rocscience, 2024) the modulus ratio (E_c/E_s) is limited to 20.

n (stress concentration ratio) = **2.74**

Stress Reduction Factor [11]

$$F_{\text{total}} = F_{\text{on soil}} + F_{\text{on column}} \quad (3)$$

$$\Delta\sigma_z A = \Delta\sigma_s (A_e - A_c) + \Delta\sigma_c A_c \quad (4)$$

Where, A_e = Influence area of one column

$\Delta\sigma_z$ = average vertical stress on the composite foundation

$\Delta\sigma_s$ = vertical stress on the soil

A_c = thickness of the soil

$\Delta\sigma_c$ = vertical stress on the column

The above equation is modified and simplified by [11] as

$$E_{\text{eq}} = [1 + (n - 1) a_s] E_s \quad (5)$$

$$\therefore E_{\text{eq}} = \frac{E_s}{\mu} \quad (6)$$

$$E_{\text{eq}} = 6756.8 \text{ kPa}$$

Where, E_{eq} is the equivalent modulus of the composite foundation

E_s is the elastic modulus of soft soil

E_c is the elastic modulus of the stone column

$$\mu \text{ is the stress reduction factor} = 1 + (n - 1) a_s \quad (7)$$

a_s is the area replacement ratio

n is the stress concentration factor

Therefore, the elastic modulus of the site's soil is modified by a reduction factor accounting for the presence of stone columns, and a new equivalent modulus will be used in the strain calculations [11].

Immediate Settlement

In calculating the immediate settlement for each layer the change in vertical stress is divided by the constrained modulus of the soft soil and is given by Equation 8 [11]:

$$\varepsilon_i = \frac{\Delta\sigma}{E} \quad (8)$$

where, ε_i = strain in sublayer i

E = constrained modulus of clay

$\Delta\sigma_i$ = change in effective stress in sublayer i

Primary Consolidation Settlement – Linear

In calculating the primary consolidation settlement, it is assumed that a foundation's settlement under a large loading is given by [11].

$$S = m_{v,s} \Delta\sigma_z h \quad (9)$$

Where, $m_{v,s}$ is the coefficient of volume compressibility of soil

$\Delta\sigma_z$ is additional vertical stress

h is the thickness of the soil layer

In the linear method for finding the primary consolidation settlement, the elastic modulus of clay is replaced with the coefficient of volume compressibility.

Carbon Footprint Computations

The basic principle of calculating embodied carbon is to multiply carbon factors for the stage of construction [12]. The Institution of Structural Engineers recommends that calculation should cover Modules A1 – A5 as minimum requirements for basic structural elements, whether substructure or superstructure [12].

Therefore, according to The Institution of Structural Engineers [12]:

Embodied carbon = material quantity (kg) * Carbon factor (kgCO₂e/kg).

Calculating the embodied footprint of a stone column made of recycled concrete aggregate and comparing it with that of a pile foundation will be done.

For comparison purposes, the same quantities were used for the stone column and pile footing.

Volume of Column (pile or stone column) = $\pi * d * L$

Where, d is diameter of column = 1 meter

L is the length of column = 10 meters

\therefore Volume of column = $\pi * 1 * 10 = 31.42 \text{ m}^3$

$$\begin{aligned} \therefore \text{Mass of Stone} &= \text{density of column} * \text{volume of column} \\ &= 1396 \text{ kg/m}^3 * 31.42 \text{ m}^3 \end{aligned}$$

$$\text{Mass of stone} = 43862 \text{ kg} = \mathbf{43.86 \text{ t}}$$

$$\begin{aligned} \text{Mass of Concrete} &= 2400 \text{ kg/m}^3 * 31.42 \text{ m}^3 \\ &= 75408 \text{ kg} = \mathbf{75.51 \text{ t}} \end{aligned}$$

According to The Institution of Structural Engineers [12]:

Carbon Factors for Stone Column = A1 – A3 (production) of sandstone = 0.06

Waste factor of sandstone = 0.111

Therefore, calculating embodied carbon of Stone column = $(43.86 (0.06 + 0.111)) = \mathbf{7.5tCO_2e}$

Carbon Factors for pile foundation = A1 – A3 (production) = 0.103

Waste factor of concrete = 0.053

Therefore, embodied carbon of pile = $(75.51(0.103 + 0.053)) = \mathbf{11.80tCO_2e}$

The analysis and implementation of the carbon footprint of this ground improvement technology have helped to reduce the amount of 4 tCO₂e that may have been emitted in the project lifecycle.

Model Validation

In verifying the outcomes of this study, a hand calculation was made using the linear method in calculating the settlement of layers under vertical stresses [13]. The outcome is plotted together in Figure 1, with the results from Settle 3 and the theoretical solution showing acceptable agreement in the total consolidation observed. There is, however, a bit of deviation, which could be attributed to the difference in the Elastic Modulus of the stone column used.

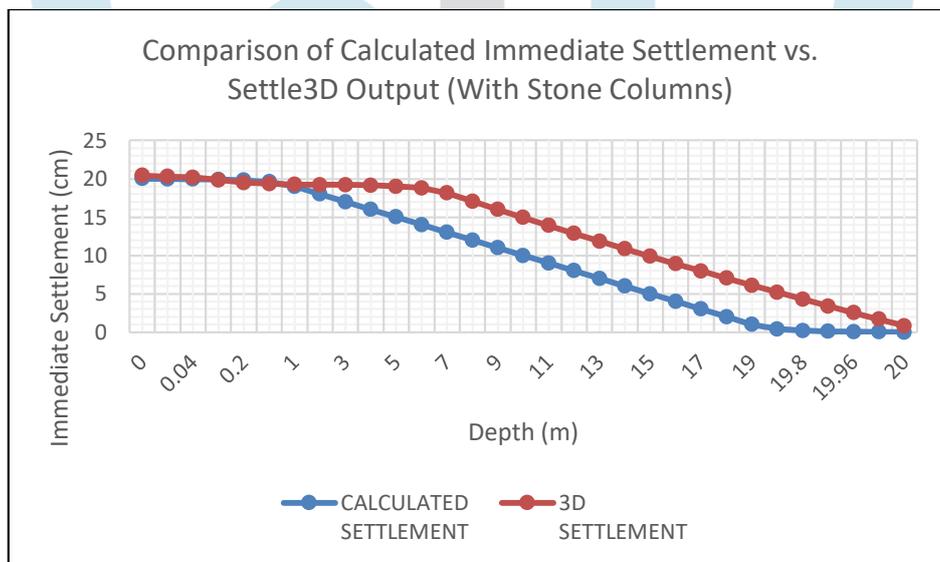


Figure 1: Settlement by Hand Calculations Vs Settle 3D Outcomes

III. RESULTS AND DISCUSSION

The initial analysis considers the soil layer purely under embankment loads, with no ground improvement by stone columns. Subsequent analysis considers the improvement effect of stone columns made of recycled concrete aggregate (RCA) on the soil. The post-ground treatment by vibro stone columns should:

- reduce differential and total settlement to acceptable levels and
- ensure the long-term performance of the treated ground.

The above criteria were therefore analyzed and discussed in relation to using recycled concrete aggregate as stone column filler material.

Total Consolidation Settlement Without Stone Column

The effect of immediate settlement on clayey soils is small to negligible [14], hence, only primary consolidation of the clayey sandy gravel soil was discussed. Soil pressure increased along the depth of the soil layer under embankment loading, and consequentially, a settlement caused by compression of the soil layer occurred along the depth. The nominal values of these settlements along the depth of the soil profile is illustrated in Figure 2, where settlement can be seen increasing with depth. From Figure 2, the maximum total consolidation is 204.2 mm, which occurs at the load's centre upon assigning a query point. Deformed contour images indicating how weak these soils are and how susceptible to settlement at the two stages of layering of the embankment are illustrated in Figure 3.

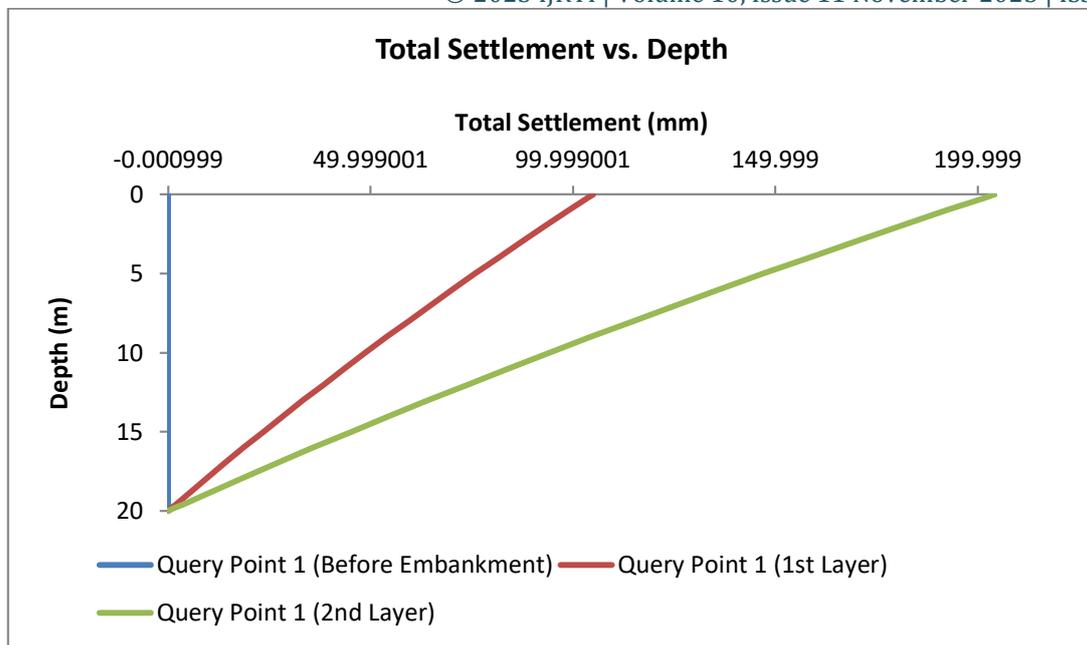


Figure 2: Graph of total consolidation Settlement in both layers vs Depth

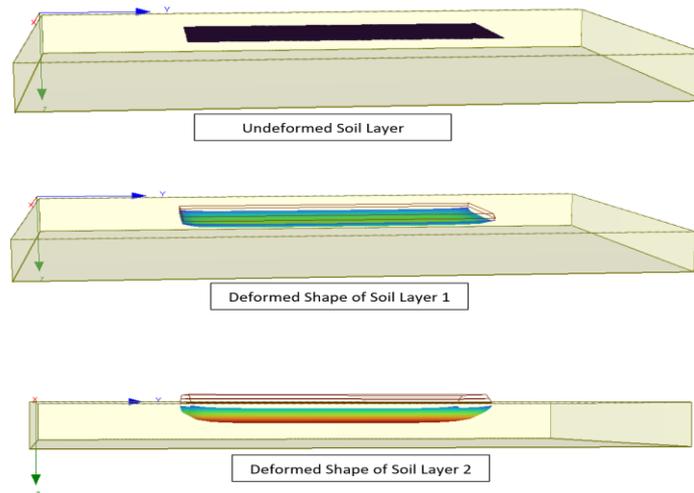


Figure 3: Contour showing the shape of soil layers

Differential Settlement Without Stone Column

Differential settlement, the difference in the total settlement at two points, or settlement beneath two foundations, was also measured by selecting two points across the face of the soil layer, which may be susceptible to soil settlement. Figures 4 indicates the value and extent of differential settlement when the clayey sandy gravel is subjected to the uniform load of the embankment. With recorded figures of 6.16 mm for layer 2 and 11.55 mm for layer 3.

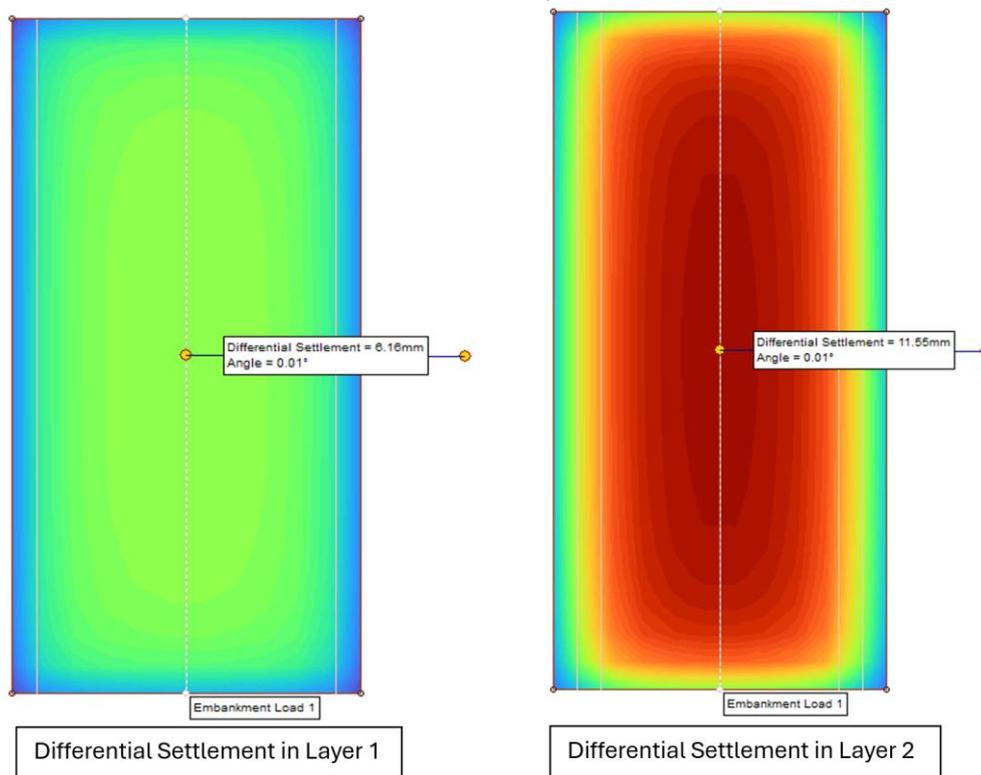


Figure 4: Contour Diagram of Differential Settlement in layer 1 and layer 2

Total Consolidation Settlement with RCA Stone Column

With the installation of recycled concrete stone columns to enhance the performance of clayey sandy gravel underlying the embankment, the total consolidation improved from 204 mm to 164 mm as shown in Figure 5 below. This represents a percentage increment in consolidation of about 19.62%. This shortens the duration it takes for consolidation settlement to take place as well as offering a more predictable way of dealing with these soils.

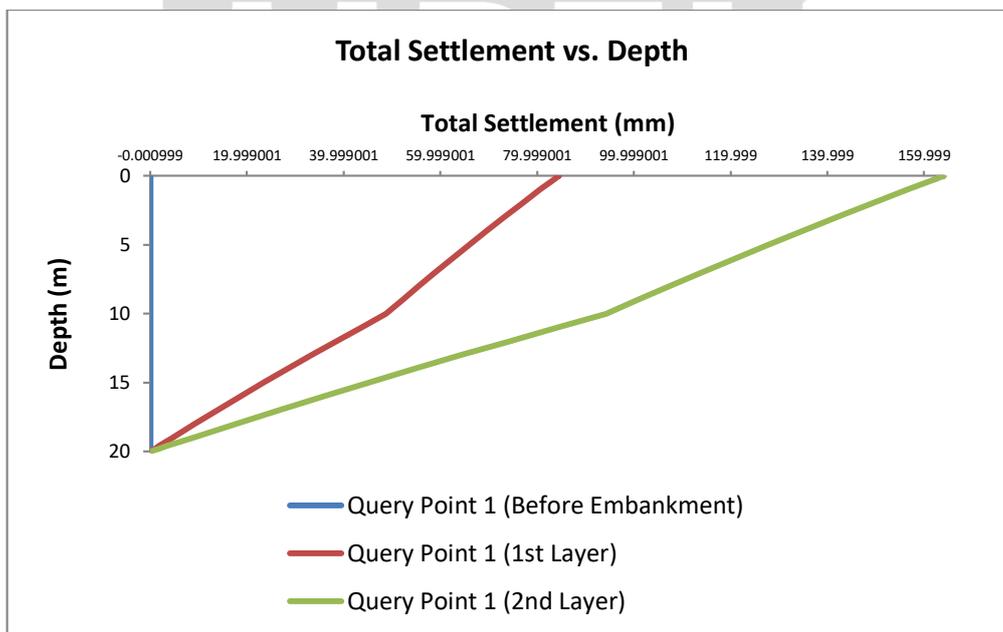


Figure 5: Illustration of Depth Vs Settlement for the three stages of loading

Differential Settlement with RCA Stone Column

With the installation of stone columns made of recycled concrete aggregate an improvement in differential settlement was also observed. A contour diagram depicting these values in both stage 2 and the final stages of embankment loading is shared in Figure 6. A decrement in differential settlement from 11.55 mm to 7.79 mm in the third stage of loading is also observed. This could be attributed to stone columns providing additional lateral stability to the formation due to its composite nature.

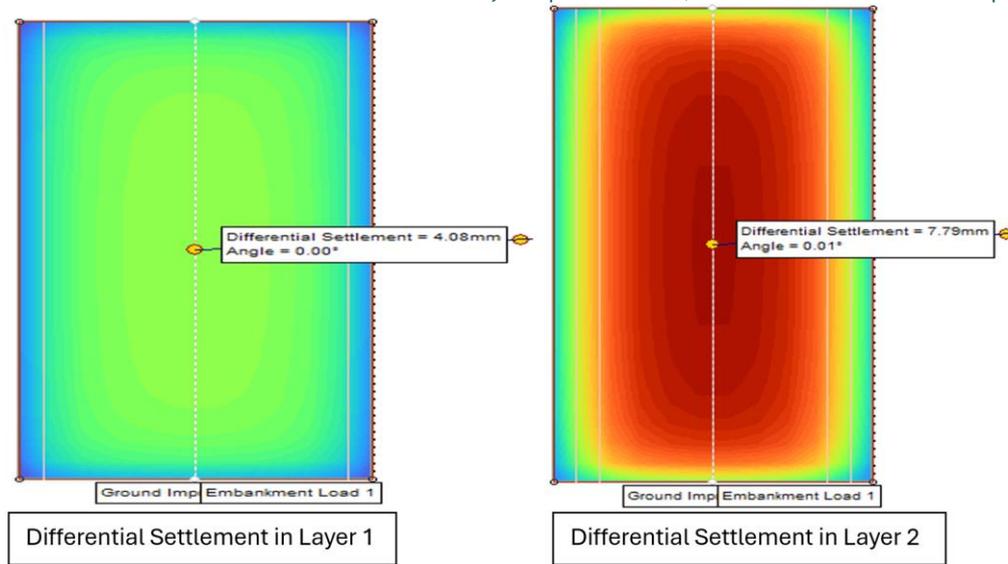


Figure 6: Showing Value of Differential Settlement with Stone Columns (Layers 1 and 2)

Sensitivity Analysis

Sensitivity Analysis was then performed on the model to evaluate and understand, holistically, how the variation of specific parameters affects the overall performance of the composite material.

Spacing Sensitivity Analysis

From Figure 7, increasing the centre-to-centre spacing between the columns also resulted in an increase in the total consolidation settlement. The reverse of this is also true, where a decrease in the spacing reduces the consolidation, this is due to a reduction in the ability of the stone columns to harness confinement and lateral stability as provided by the surrounding soils.

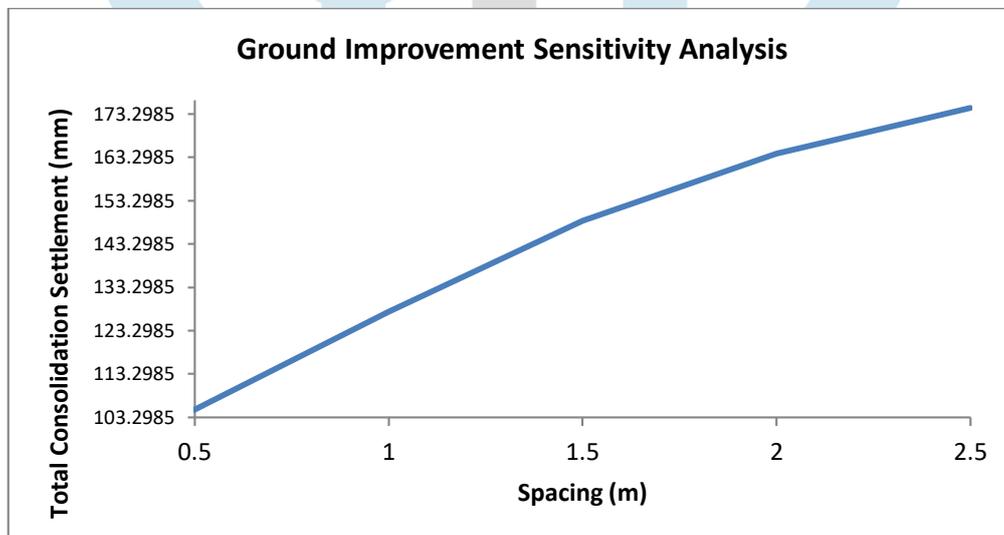


Figure 7: Variation in centre to centre spacing of columns against total consolidation

Bottom Depth Sensitivity Analysis

Increasing the bottom depth of the column also results in a decrease in total consolidation from 204.4 mm to about 199.94 mm. Figure 8 is a graph showing this decrease in consolidation with depth. This is because, as the stone column bottom depth goes deeper, more soil layers are also improved.

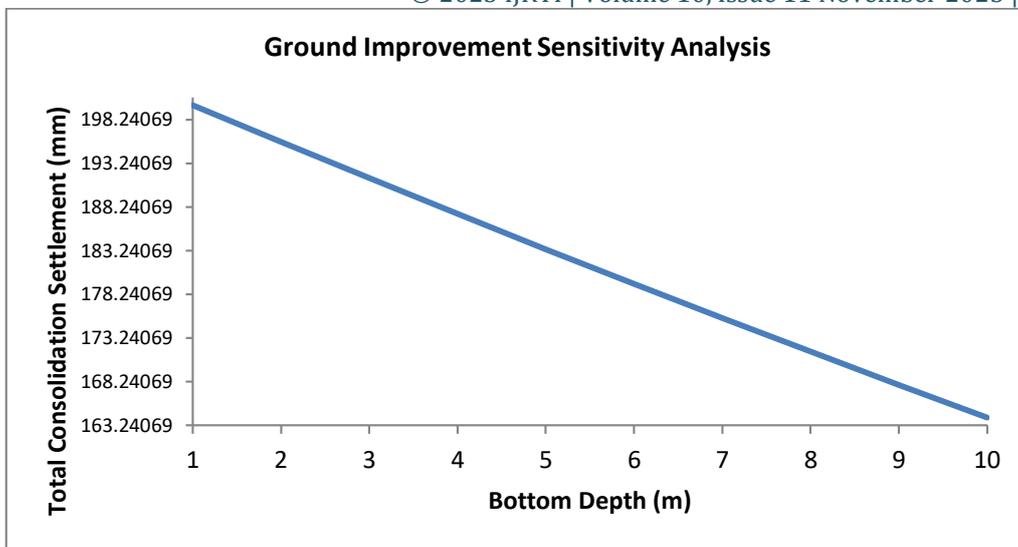


Figure 8: Graph of Bottom Depth Sensitivity Analysis

Stone Columns as Drainage

An analysis of the potential of using stone columns as a drainage option to aid in the dissipation of excess pore water pressure was also explored. Due to challenges with Settle3's inability to include the drainage option to the already described model above, a new model with rectangular loading was developed for this analysis. As shown in Figure 9, a significant increment from 256 mm to about 647 mm in total consolidation with the inclusion of the stone column as drainage. This could be attributed to the stone columns acting as vertical drainages to help dissipate the excess pore pressure water, hence consolidation happening faster than without the drainage option. This aids in the better analysis of the formation's settlement characteristics. Consequently, a graph showing excess pore pressure against depth over the construction period shows the pressure bulb significantly reducing after just 0.083 years of loading the soil.

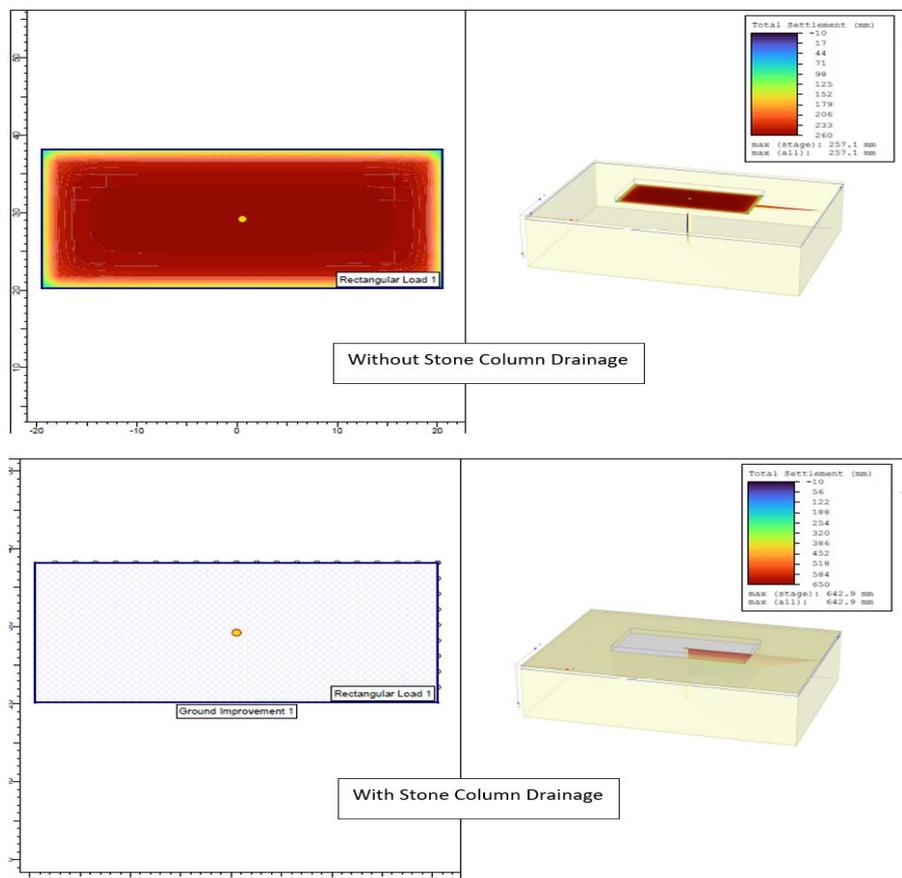


Figure 9: Values of Total Consolidation with and without Stone Column as Drainage

As can be seen in Figure 10, it takes more years, about 22.1739 years, to achieve 95 % consolidation without the stone column as drainage. However, it takes about only 6.21088 years to achieve the same amount of consolidation using stone columns as drainage options.

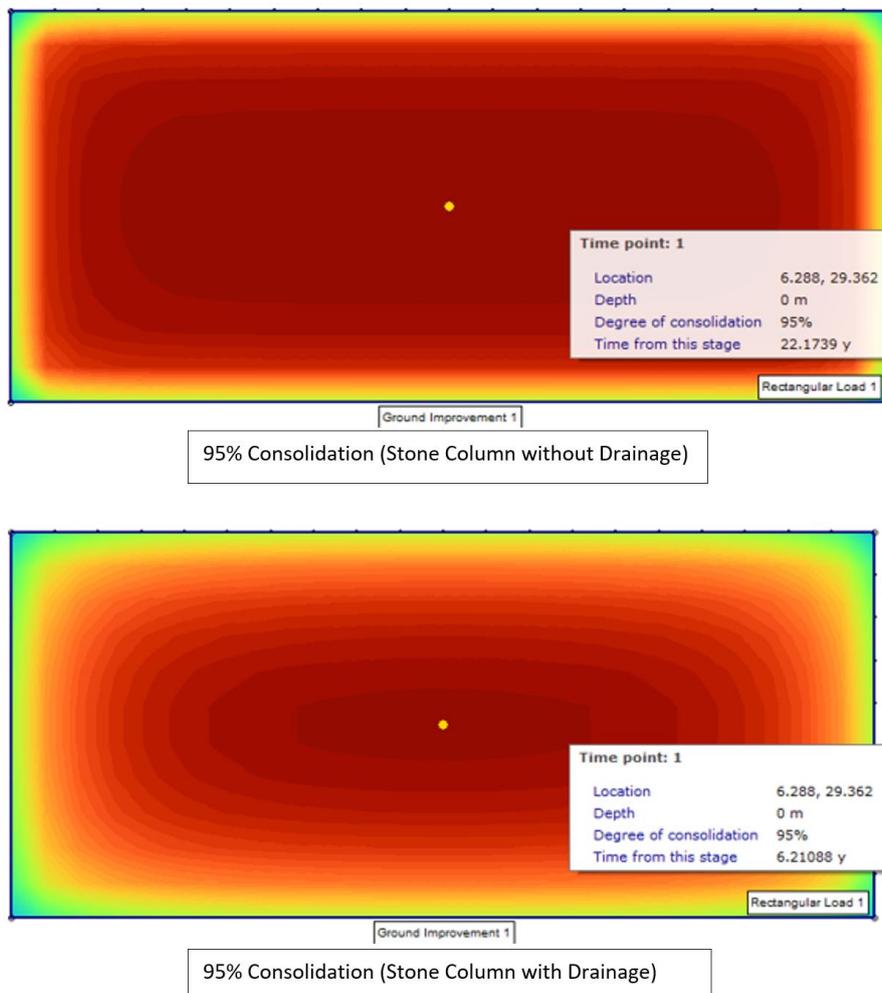


Figure 10: Query of Time to Reach 95% Consolidation (Stone Column without and with Drainage)

IV. CONCLUSION

Stone columns have, over the years, been used to improve the geotechnical properties of weak soil. The granular materials of stone columns are usually sourced from quarry sites, which makes them environmentally unfriendly and unsustainable. This study, therefore, sought to investigate the geotechnical viability of using recycled concrete aggregates as stone column filler material to improve the settlement characteristics of the head deposit of South-Central Leeds while evaluating their environmental significance.

The findings from the numerical analysis showed a general improvement in the settlement characteristics of the soil when reinforced with stone columns, as total consolidation settlement was reduced by 19.62 % and differential settlement reduced from 11.55 mm to 7.79 mm.

Furthermore, the time taken for the formation to reach a 95 % consolidation also reduced from 22.1739 years to 6.21088 as the stone columns served as vertical drainage. Sensitivity analysis performed on the stone column reinforced soil also showed that increasing the spacing between the columns increased consolidation, while increasing the bottom depth of the column decreased total consolidation from 204.4 mm to about 199.94 mm.

The analysis also proved the environmental significance of using stone columns as there was a 4 tCO₂e carbon credit compared to typical pile foundations. These outcomes indicate that recycled concrete aggregates are competent in improving the in-situ head deposits of South-Central Leeds and are environmentally sustainable.

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