A Ground Improvement Case Study Using Soil Replacement or Stone Columns Using Settle3 and RS3

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Abstract. Stone Columns were first introduced approximately 60 years ago as a technique for improving both cohesive soils and silty sands. Its construction involves the partial replacement of unsuitable soils with a pattern of compacted vertical columns of stone. In the settlement analysis software, Settle3, a Stress Reduction Method is used for computing the settlement under the composite stiffness of soil and stone columns. This study provides a settlement analysis of a case study with ground improvement using stone columns. The same model was created using a 3D FEM analysis software, RS3, to calculate the settlement. The results of the case study show a good agreement using both 3D FEM and the simplified settlement analysis using Settle3 software considering the same assumptions in both software. Also, the stress concentration ratio of stone columns and soil stiffness are also discussed in the models.

Keywords: Ground improvement · stone columns · FEM · settlement analysis · Settle3

1 Introduction

The Stone column reinforcement has been used in soil layers including weak soil deposit and layers such as peat all around the world over the last three decades (Black et al., 2007). They're used to increase the load-carrying capacity and reduce settlement of structural foundations. Advanced technique over the years have improved this method to apply stone columns to greater depths of up to 30 m (Black et al., 2007). The overall performance of stone columns is governed by the lateral support which is provided from the surrounding soil. Due to the earth pressure that increases per depth, this will then increase the performance of stone column as well along the depth of soil. In weak deposits where lateral support is low, the building effect may occur from the stone columns. Thus, accurate assessment of column bulging effect along with soil stiffness becomes imperative in making the load transfer to stone column and load-carrying capacity is enhanced with the effect of stone columns.

The motivation of this study involves investigating improvement of settlement in building profile located in Pompano Beach, FL, USA. The structural component along

R. E. Hammah et al. (Eds.): RIC 2023, AHE 19, pp. 439–449, 2023.
https://doi.org/10.2991/978-94-6463-258-3_44

with plan drawing is provided. The target total settlement and differential settlement requirement for the project is specified in the model description. Given the demand of growing interest in use of stone columns for ground improvement, the paper outlines two ways in which engineers can use the settlement analysis software to apply this concept in simulation. First method involves using soil replacement using equivalent composite stiffness, while the second method uses stone column reinforcement proposed by Jie Han (2012). More details on the model and the properties used for the soil and stone columns are provided.

After the methods of ground improvement, the settlement analysis is compared with 3D Finite Element software to provide comparison between the methods, and both are in reasonable agreement with each other. The difference may be explained by different methods in calculating the stress-strain relationship, but they can be improved by multiple methods which is discussed in results section of the paper.

2 Model Description

The proposed study involves calculating ground settlement due to structural foundation loads in Pompano Beach, FL, USA. The loading conditions involve heavily loaded mat foundations with contact pressures under the mats of up to 300 kPa. Mat foundation 6 was selected for settlement analysis with dimensions of 17 feet by 10 feet. Figure 1 shows the full plan view of the ground floor and foundation.

Using structural analysis software SAFE, the above-mentioned loading conditions are analyzed and the soil pressure diagram with load combination of 100% DEAD + 50% LIVE load is shown in Fig. 2.

The loading condition for Mat 6 which is located on the bottom right corner of the plan is then transferred to soil settlement analysis software, Settle3 with soil layers shown in Fig. 3.

Since the contact pressure under the mat is variable, several polygonal loads have been used in Settle3, which allow users to have different loads at the vertices of the load.

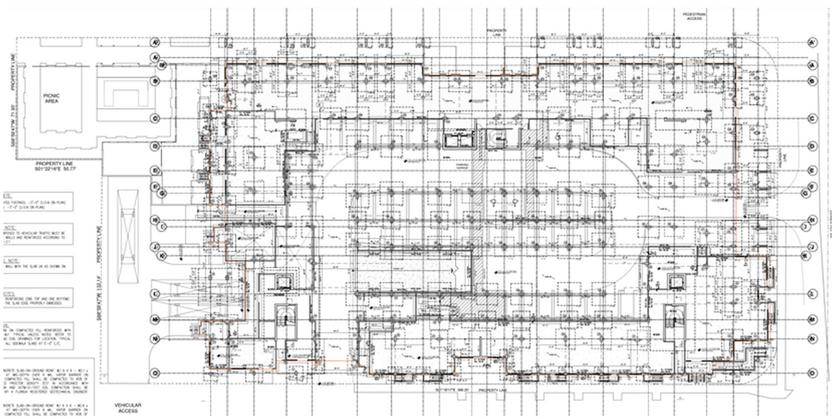

Fig. 1. Detailed plan view drawing of mat foundation and ground floor in Pompano Beach FL, USA.

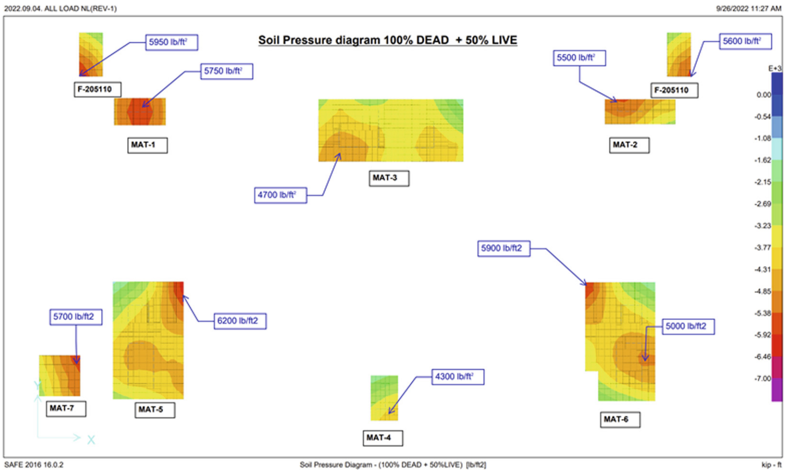

Fig. 2. Soil pressure from loading conditions of mat foundation ground floor.

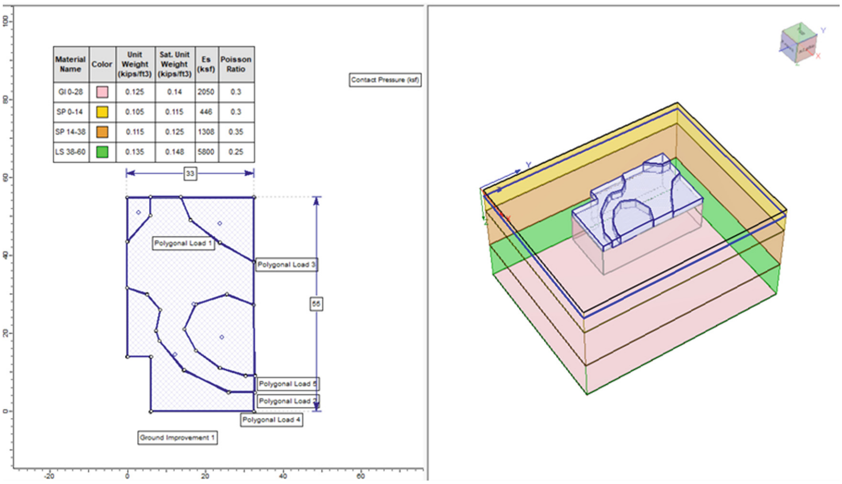

Fig. 3. Ground improvement feature using soil replacement in Settle3.

As shown in the model, the soil material layers used for this model are displayed in Table 1.

The settlement criterion is the following: 1 inch total and ½ inch differential settlement. Below shows the typical soil profile and parameter used for the settlement analysis (Table 2).

The ground improvement has been used to calculate the expected settlement. The purpose of the settlement analysis is to determine the number of aggregate piers and treatment depth under Mat-6 foundation.

Another method which users can use ground improvement in Settle3 is the stone column feature. This feature allows users to apply reinforcement with stone columns by

Table 1. Soil properties for each layer in Settle3

Material	Unit weight (kips/ft^3)	Sat. Unit weight (kips/ft^3)	Es (ksf)	Poisson's ratio
Composite ground improvement soil layer	0.125	0.14	2050	0.3
Loose Sand	0.105	0.115	446	0.3
Dense Sand	0.115	0.125	1308	0.35
Limestone	0.135	0.148	5800	0.25

Table 2. Soil layer and its corresponding material properties.

Top EL (feet)	Layer Number	USCS Type	Top (feet)	Bottom (feet)	N60 (bpf)	ɣb (pcf)	Es (psf)	μ	Ds (psf)	Φ (deg)	Su (psf)
6.5	1	SP	0	14	11	105	445,710	0.3	600,000	31	0
−7.5	2	SP	14	38	23	115	1,308,460	0.35	2,100,000	34	0
−31.5	3	LS	38	40	50	135	5,800,000	0.25	6,960,000	40	0

taking consideration of the composite effect on soil stiffness. Figure 4 shows the model with Stone columns applied instead of equivalent soil replacement method.

The loads have been applied also in 3D FEM analysis software using RS3, along with soil profile as shown in Fig. 5.

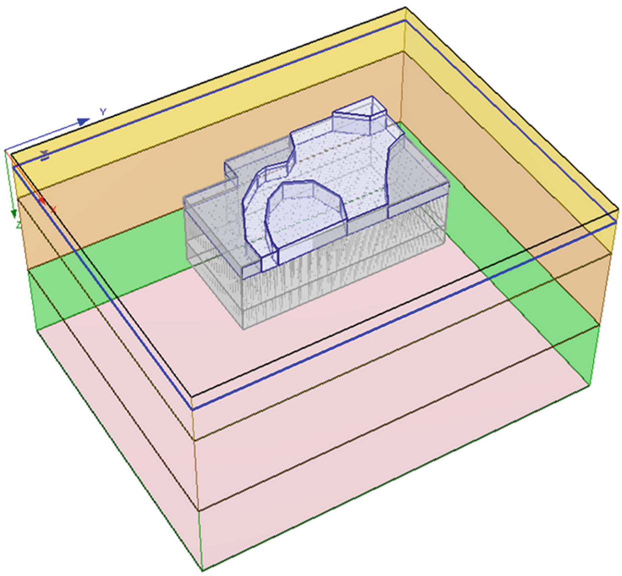

Fig. 4. Stone column under the structural loads in Settle3.

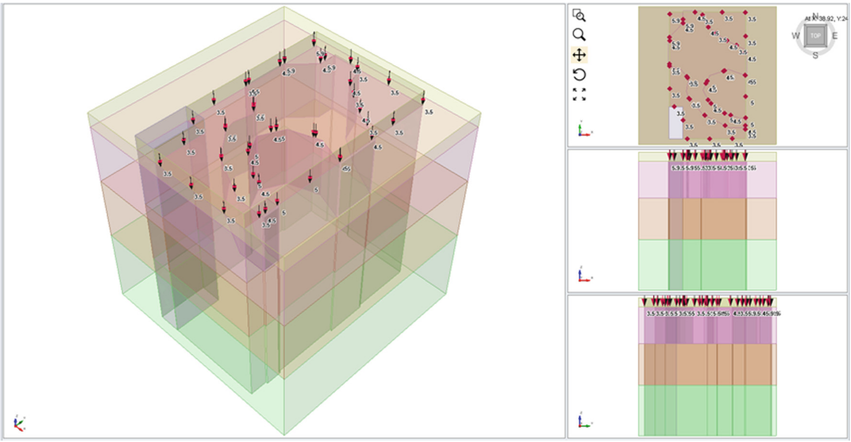

Fig. 5. Loading condition for RS3 model.

The restraints are applied with x,y,z along the sides to calculate the settlement in 3D analysis. As the nature of FEM analysis with 3D space is challenging to replicate, the results between two programs are within reasonable agreement with each other (Fig. 6).

Mesh conditions used in RS3 are shown below in Fig. 7.

The results comparison between settlement analysis using Settle3 and RS3 is provided in the next section. Settle3 uses immediate settlement with Westergaard's stress computation while RS3 uses 3D Finite Element Method (FEM). With results comparisons between two models, it provides a reasonable estimate for settlement analysis result.

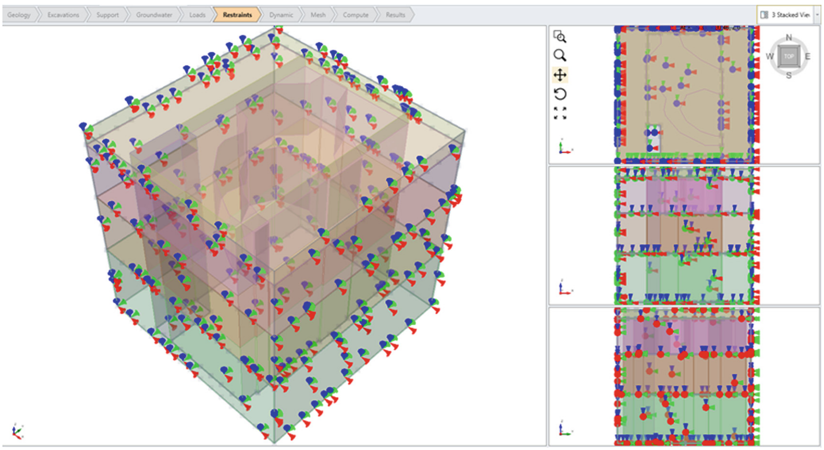

Fig. 6. Restraint condition for RS3 model.

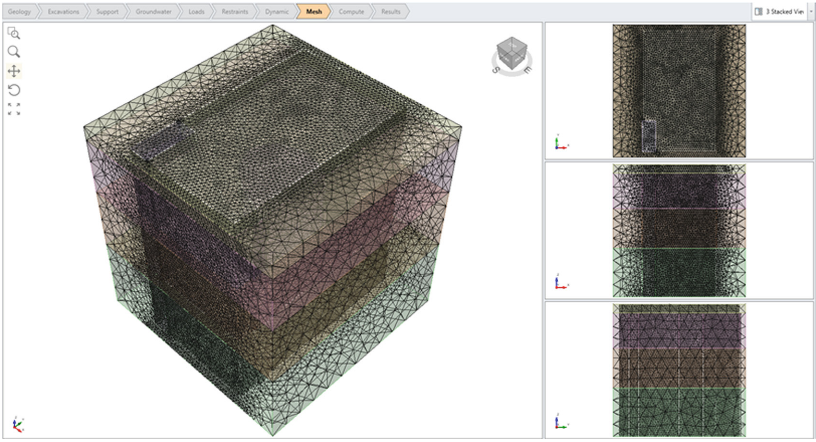

Fig. 7. Mesh condition for RS3 model.

3 Results and Discussion

Settlement analysis using Settle3 shows immediate settlement analysis with the loading conditions shown in model description section (Fig. 8).

The total settlement without ground improvement region applied is 1.69 inches. Also, the settlement at the mid-point of the variable load shows maximum differential settlement of 0.53 inches.

The target total settlement for acceptable range of this model is below 1 inches of total settlement with less than 0.5 inches of differential settlement. There are three ways on how this can be achieved in ground improvement simulation using Settle3. The first method involves applying ground improvement as soil replacement where the regions the user specifies will be replaced by another soil layer property. This would be replacing the whole region by the user-specified, equivalent composite stiffness. Below is the soil replacement used with Constrained Young's modulus of Es = 2050 ksf which is applied at top depth of 4 feet and extends to 20 feet in depth (Fig. 9).

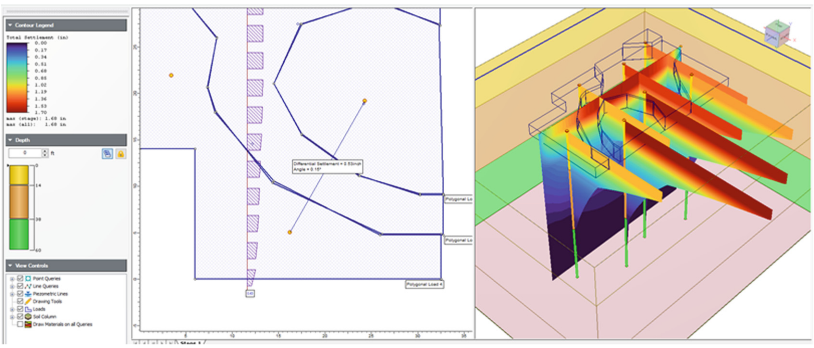

Fig. 8. Immediate settlement analysis result using Settle3 without ground improvement.

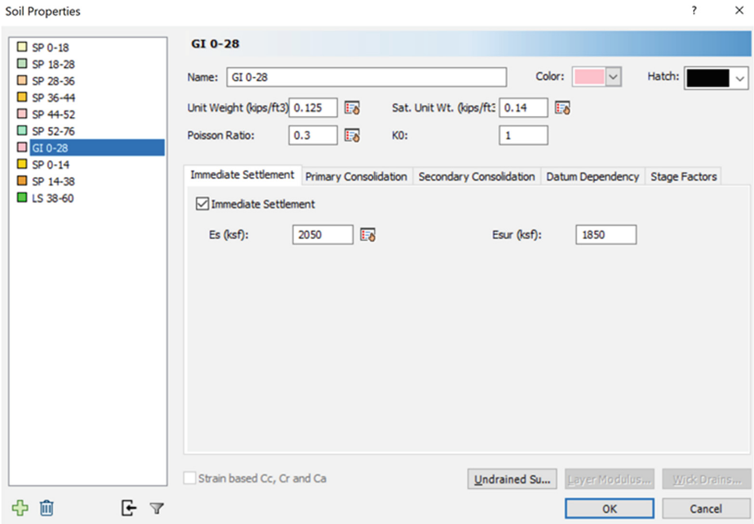

Fig. 9. Soil replacement material property.

After applying the soil replacement method, the resulting settlement reaches to 0.79 inches (Fig. 10).

It also shows the differential settlement is around 0.24 inches. Compared to the previous model without ground improvement, the soil replacement with Es = 2050 ksf replaced under the loading zone with depth of 16 feet deep resulted in settlement to be within acceptable limit.

The second method which the users can use to simulate ground improvement is to use stone columns. By using stone columns, the user would not be replacing the whole region by another soil, but they will be using the composite stiffness calculated with the soil stiffness and stone column stiffness (Fig. 11).

After the stone columns are applied, the settlement analysis result and differential settlement analysis result are under the target total settlement criterion (Fig. 12).

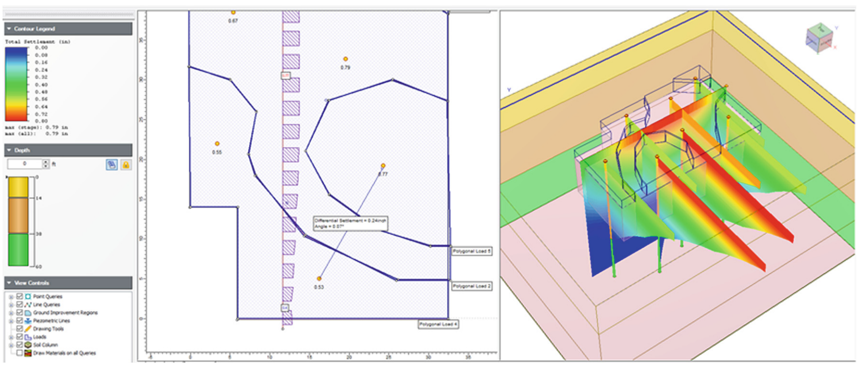

Fig. 10. Settlement analysis after the soil replacement in Settle3.

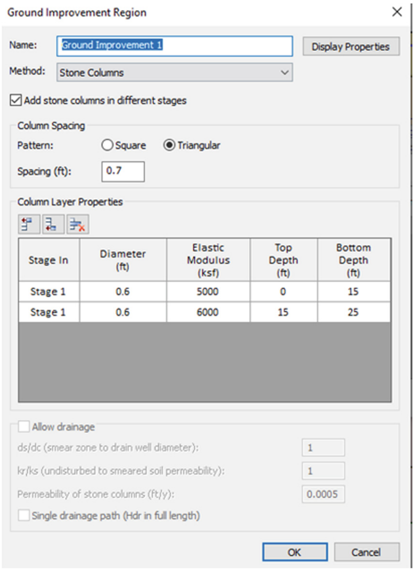

Fig. 11. Stone column with different stiffness along depth of soil.

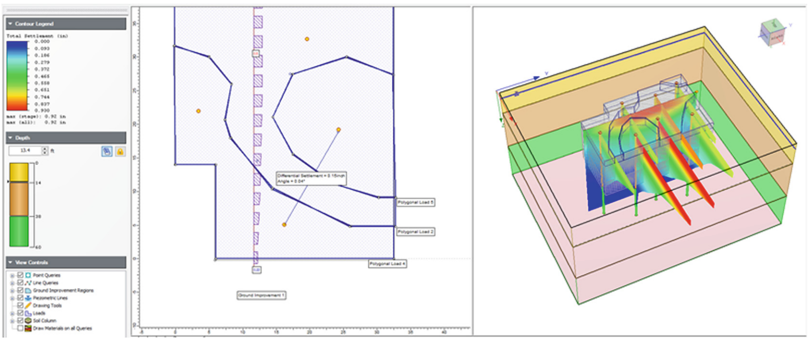

Fig. 12. Settlement analysis and differential settlement

The result shows 0.15 inches for differential settlement with total settlement of 0.92 inches. The sensitivity analysis shows that by increasing the stone column stiffness or increasing the depth of reinforcement will further improve the settlement as shown in Fig. 13.

Therefore, using stiffer column can improve the settlement by 0.7 inches. If the user wants to see the spacing effect, this can also be done as well in Settle3 (Fig. 14).

This goes onto show how decreasing the spacing between the columns will also improve settlement to approximately 0.8 inches.

There are more way Settle3 can be used to optimize the design while meeting the target total settlement and differential settlement. When considering increasing the stiffness

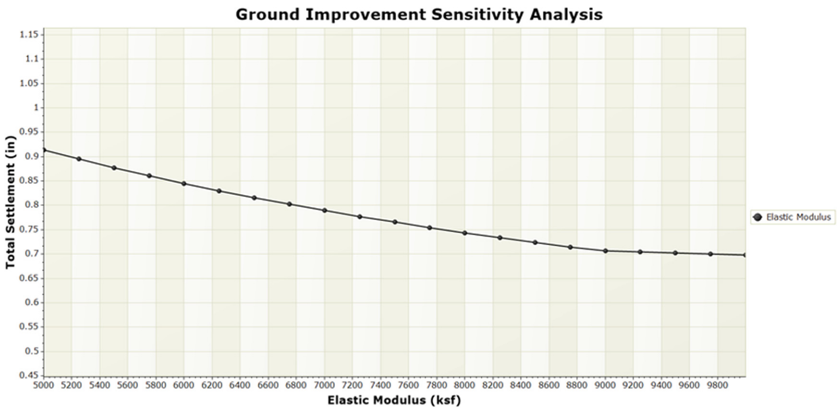

Fig. 13. Sensitivity analysis of stone column stiffness and its impact on total settlement.

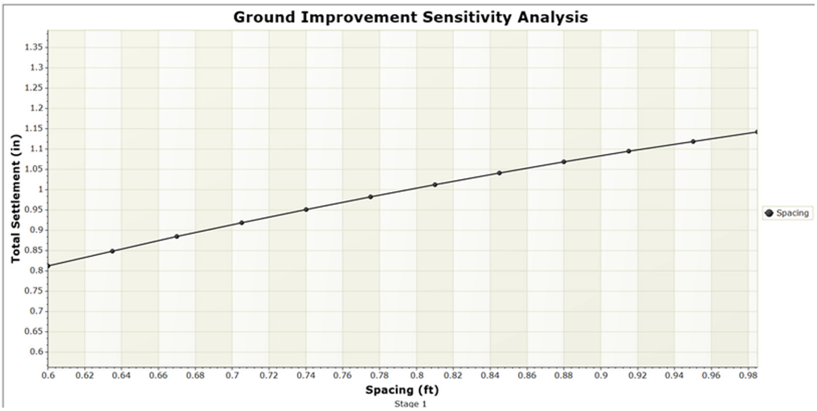

Fig. 14. Spacing effect on total settlement for stone columns in Settle3.

of stone columns, there is a maximum stress concentration ratio between the stiffness soil and stone columns with the empirical equation provided by Jie Han (2012).

The stress concentration ratio is calculated based on the following expression:

$$n_s = 1 + 0.217\left(\frac{E_c}{E_s} - 1\right) \quad (1)$$

where E_c is the elastic modulus of the columns, and E_s is the elastic modulus of soil. Based on the field data, the modulus ratio of (E_c/E_s) should be limited to 20 (Jie Han, 2012) as shown in the Fig. 15.

Therefore, there will be a threshold stiffness where no settlement improvement is shown with respect to increase in stone column stiffness.

The same condition with equivalent soil replacement has been applied in RS3 for comparative analysis. Figure 16 shows the total settlement under the same loading condition.

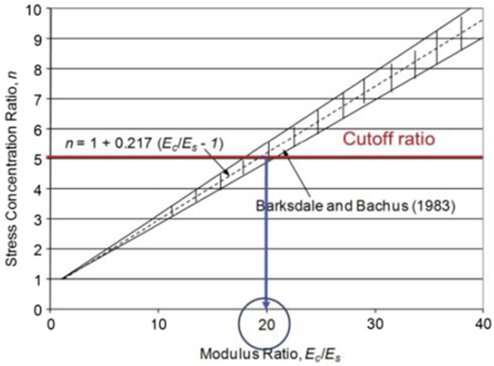

Fig. 15. Stress concentration ratio of stone column to soil with cut-off ratio.

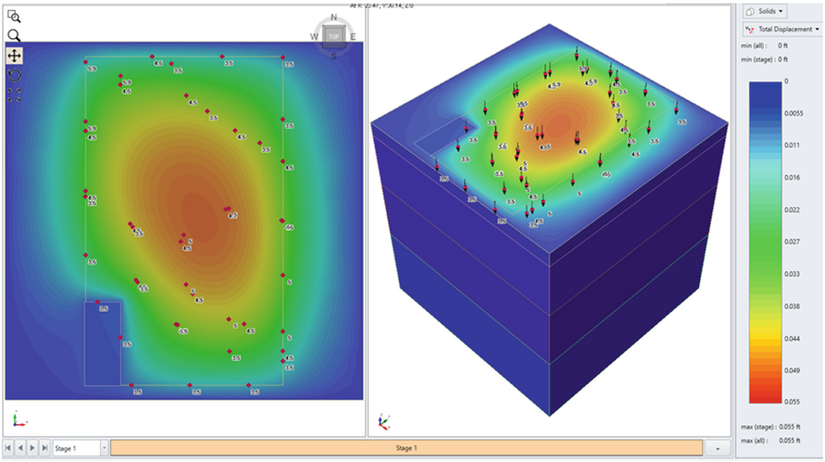

Fig. 16. 3D FEM model settlement results using RS3

The resulting settlement yields around 0.055 ft, equivalent to 0.66 inches. This is in reasonable agreement with Settle3 which yielded settlement of 0.79 inches. As mentioned previously, two models are created with different modelling approaches and analysis methods used. One is using FEM method with restraints applied in all sides. However, Settle3 is using Westergaard's stress method with immediate settlement analysis. More details on how the settlement is calculated for both programs can be found in Rocscience documentation (Settle3, 2023 & RS3, 2023). These difference in the result may improve if larger soil expansion factor is used with respect to the applied loading region.

4 Conclusion

The case study of improving ground settlement with respect to structural foundation loads have been investigated using Settlement analysis software Settle3 and 3D FEM program RS3. Two main methods of ground improvement have been provided in this paper: soil replacement and stone columns. Soil replacement provide an easy way to manipulate the ground condition with equivalent composite stiffness of improved soil condition for improving ground settlement. However, this method leaves challenge for the designer or engineer to come up with equivalent stiffness of the improved ground. On the other hand, stone column feature in Settle3 allow the engineers to define the stone column properties such as stiffness, spacing, and depth of the columns. The discussion on stress concentration ratio of the stone column stiffness to soil stiffness is discussed. The comparison between the settlement using Settle3 and 3D FEM analysis provides more confidence in the analysis result, and both showed reasonable agreement with each other. Further studies involve more in-depth analysis on optimization of the parameter used in the stone column properties as well as boundary conditions used in 3D FEM analysis.

References

Barksdale, R. D., & Bachus, R. C. (1983). Design and Construction of Stone Columns. Design and Construction of Stone Columns (Vol. 1, pp. 1–3). Washington D.C., VA: Federal Highway Administration.

Black, Jonathan & Sivakumar, Vinayagamoorthy & Madhav, Madhira & Hamill, Gerard. (2007). Reinforced Stone Columns in Weak Deposits: Laboratory Model Study. Journal of Geotechnical and Geoenvironmental Engineering - J GEOTECH GEOENVIRON ENG. 133.https://doi.org/10.1061/(ASCE)1090-0241(2007)133:9(1154)

Han, J. (2015). Principles and Practice of Ground Improvement. John Wiley & Sons, Inc.

Mokhtari, Masoumeh & Kalantari, Behzad. (2012). Soft Soil Stabilization using Stone Columns—A Review. 17.

Ng, K. S., & Tan, S. A. (2015). Simplified homogenization method in stone column designs. Soils and Foundations, 55(1), 154–165.

RS3 (2023) 3D Finite Element Software for advanced analysis. Rocscience Inc.

Settle3 (2023) "Ground Improvement Feature: Verification of settlement calculation for stone columns." Rocscience Inc.

Settle3 (2023) Soil Settlement and Consolidation Analysis. Rocscience Inc.

Settle3 Theory Manual (2023).