SLOVAK JOURNAL OF CIVIL ENGINEERING

Vol. XIX, 2011, No. 3, 17 – 21

J. PIVARČ

STONE COLUMNS – DETERMINATION OF THE SOIL IMPROVEMENT FACTOR

Ján PIVARČ
jan.pivarc@stuba.sk
Research field: stone columns

Address: Department of Geotechnics,
Faculty of Civil Engineering
Slovak University of Technology,
Radlinského 11, 813 68 Bratislava

ABSTRACT

A stone column is one of the soil stabilizing methods that is used to increase strength, decrease the compressibility of soft and loose fine graded soils, accelerate a consolidation effect and reduce the liquefaction potential of soils. The columns consist of compacted gravel or crushed stone arranged by a vibrator. This paper deals with Priebe`s theory (1976) on the design of an improvement factor, which belongs among the most used analytical methods and also describes the numerical and laboratory models of stone columns. The improvement factors calculated from numerical and laboratory models are compared with the improvement factors resulting from Priebe´s theory.

KEY WORDS

- *Stone column,*
- *design,*
- *laboratory model,*
- *numerical model.*

INTRODUCTION

Vast areas covered with thick layers of fills or with layers of soft clay deposits are not suitable for the construction of a foundation. With the increasing size of urban areas and industrial zones it is necessary to consider the possibilities of realizing foundations on these areas. Ground improvement techniques are normally preferred for economic considerations. Out of several techniques available, stone columns belong among the most preferable and are also widely used. This ground improvement technique has been successfully used to increase bearing capacity and reduce the settlement of constructions such as storage tanks, earthen embankments, raft foundations, etc. Their main advantage lies in improving the soil properties below a structure (raft and depth) and following the reduction of an irregular settlement.

In spite of the wide use of stone columns and their development in construction methods, present design methods are empirical, and only limited information about designing stone columns are available in technical codes.

The stone column technique was adopted in European countries in the early 1960s. Stone columns in compressive loads fail in 2 main different modes: bulging (Hughes and Withers, 1974) [1] and general shear failure (Barksdale and Bachus, 1983) [2]. McKelvey, et al. (2004) [3] carried out experimental studies on a group of five stone columns and reported that the central column deformed or bulged uniformly, while the edge columns bulged away from the neighboring columns. Many researchers have developed theoretical solutions for estimating the bearing capacity and settlement of foundations reinforced with stone columns. Priebe (1995) [4] proposed a method for estimating the settlement of foundations resting on an infinite grid of stone columns. The basic for this method is the unit cell concept. In this concept, Priebe considered the area of soil surrounding a stone column at a distance depending on the spacing of the columns. As all the columns are simultaneously loaded, it is assumed that a lateral deformation in the soil at the boundary of the unit cell is equal to zero. The settlement improvement factor is derived as a function of the area ratio of the whole unit cell and stone columns and the angle of internal friction

SLOVAK JOURNAL OF CIVIL ENGINEERING

2011/3 PAGES 17 — 21

Tab. 1 *Properties of materials used in the experiments.*

Material	w (%)	E_{def} (MPa)	μ	c_u (kPa)	φ (°)	$\gamma_{d,max}$ (kN/ m^3)	γ (kN/ m^3)
S5-SC	16	3.1	0.35	16	24	16.01	14.97
G2-GP	0	45	0.2	0	45	17.36	16.52

of the column material. With the exception of the area near the edges of the loaded area, the behavior of the stone columns is the same; thus, only one column unit needs to be analyzed.

This study is focused on a comparison of numerical, analytical and laboratory model settlements to estimate the improvement factor of soil improved by stone columns. All the models in this study were prepared by the vibro replacement method, which means that soil is removed from a hole and not compacted to the sides such as in the vibro displacement method.

LABORATORY MODEL

The laboratory experiments were carried out using stone columns with diameters of about 60 mm and lenghts of 300 mm, 420 mm and 540 mm. All the laboratory experiments were performed with stone columns surrounded by clayey sand, S5–SC according to STN 73 1001, in cylindrical test boxes with a height of 600 mm and with variable inner diameters from 125 mm to 253 mm. The cylindical boxes represent the required area of a unit cell around a stone column. A triangular pattern of stone columns was under consideration. Testing of the stone columns was carried out with soil parametres acquired from laboratory tests of samples removed from the cylindrical test boxes after compaction of the soil. The stone columns were modeled as a floating unit in the soil space; that is, the bottom part of the longest column is about 1 d, or, about 60 mm from the bottom of the test box. Because the stone column has relatively less stiffness in comparison to a conventional pile and also because a horizontal deformation is more expected than a vertical one, the distance of the stone column of about 60 mm from the bottom of the test box is adequate. The ratios of the length of the stone columns to the diameter of the stone columns l/d are modeled as 5, 7 and 9. The test was carried out in a test box filled with clayey sand S5–SC with a total cohesion cu = 16 kPa. The humidity of the soil in the box was set before testing, so an appropriate quantity of clean water was poured into dry soil. Every experiment was realized with the same humidity of soil of about 16%. All the samples were left for at least 24 hours for saturation before putting them into the boxes and compacting and forming the stone column (fig. 1, 2). The stone columns were formed from gravel, which was classified according the STN 73 101 as G2 – GP. The fractions of the gravel were from 2 mm to 5 mm. All the soil and gravel properties are seen in table 1.

After the formation of the stone columns, the “load – settlement“ behavior of the improved complex was observed. A rigid 10 mm thick steel plate was used as a loading plate. The loading was applied by a compactor with a constant velocity of 5 mm/min. Thus, the increased force and deformation were observed by electronic sensors at intervals of 1 sec. The left side of figure 3 shows the final shape of the stone column when the whole complex of the stone column and surrounding soil was loaded. On the right side the final shape of the column is deformed by bulging when only that area of

Fig. 1 *Compacting of soil prepared for the formation of the stone columns.*

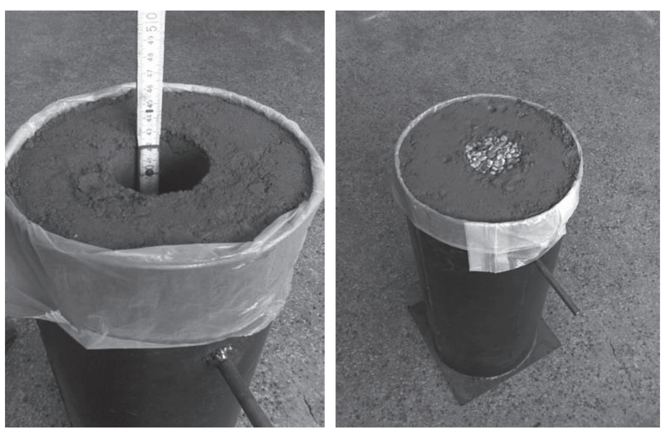

Fig. 2 *Installing a stone column into the soil and a compacted stone column.*

SLOVAK JOURNAL
OF
CIVIL ENGINEERING

2011/3 PAGES 17 — 21

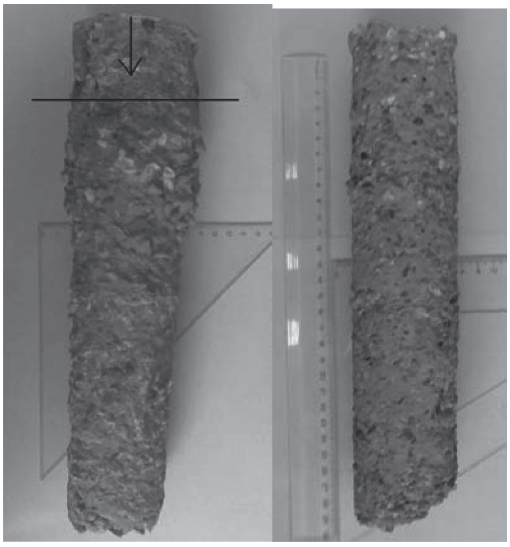

Fig. 3 *Shape of the failed stone column after the area of SC was loaded; the whole area of the SC and surrounding soil was loaded (equivalent area).*

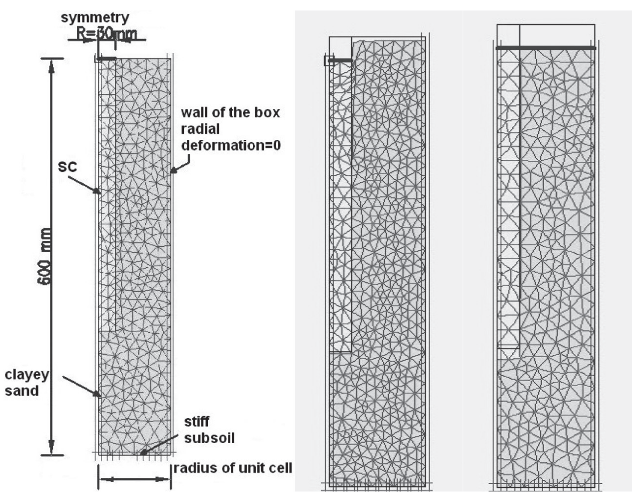

Fig. 4 *FE meshing and typical deformed mesh after SC loaded and equival area loaded.*

Tab. 3 *Factor of improvement of soil.*

s/d	Factor of improvement - *μ*
2	2.43
3	1.67
4	1.36

the stone column was loaded. This subexperiment was carried out to verify the influence of the loading area on the deformation of the stone columns. The results are in good agreement with the results of Hughes and Withers [1].

Table 2 summarizes the settlements of the SC after various pressures were applied. Because the behavior of the soil under a loading plate in the cylindrical test boxes is similar to that of an oedometer, the oedometric modulus of the improved soils for different spacing/diameter ratios was calculated. All the results, including the oedometric test of the unimproved soil, are summarized in table 2. Table 3 shows the final soil improvement factor with the stone columns calculated like the settlement ratio of the unimproved to improved soil.

NUMERICAL MODEL

For the numerical modeling of the stone columns in cylindrical test boxes, the Mohr Coulomb elastic prefect plastic criteria for modeling soil was chosen using PLAXIS V8 software. Fifteen node elements were applied. The finite element (FE) meshing is shown in figure 4. The boundary conditions along the vertical boundaries of the axially symmetrical model are fixed for the lateral deformations. The boundary condition allows vertical deformation. Fig. 4 also shows a typical deformed mesh after loading only the stone column area and a typical deformed mesh after loading the equivalent area of the stone column.

All the soil and gravel properties used in the numerical model are summarized in table 1.

Tab. 4 summarizes the settlements of the SC complex after various pressures are applied, similarly to tab. 2. Table 5 shows the final soil improvement factor with the stone columns.

Tab. 2 *Settlements of SC after various pressures and the oedometric modulus.*

Experiment	*s/d*	Diameter of loading plate (m)	Settlement for 50 kPa (m)	Settlement for 100 kPa (m)	oedometric modulus (MPa)
Equivalent area loaded	2	0.115	0.0021	0.00582	8.06
Equivalent area loaded	3	0.181	0.00314	0.00945	5.10
Equivalent area loaded	4	0.243	0.00492	0.012	4.24
Oed. test– unimpr. soil					3.1

SLOVAK JOURNAL OF CIVIL ENGINEERING

2011/3 PAGES 17 — 21

Tab. 4 *Settlements of SC after different pressure and oedometric modulus.*

Experiment	s/d	Diameter of loading plate (m)	Settlement for 50 kPa (m)	Settlement for 100 kPa (m)	oedometric modulus (MPa)
Equivalent area loaded	2	0.125	0.00397	0.00802	7.96
Equivalent area loaded	3	0.191	0.00562	0.01130	5.34
Equivalent area loaded	4	0.253	0.00664	0.01364	4.29
Equivalent area loaded with no SC	4	0.253	0.0150	0.0245	3.16

Tab. 5 *Soil improvement factor.*

s/d	Factor of improvement - μ
2	2.52
3	1.69
4	1.36

Tab. 6 *Soil improvement factor.*

s/d	Factor of improvement - μ
2	2.76
3	1.69
4	1.39

ANALYTICAL DESIGN ACCORDING TO PRIEBE

This approach includes one column and the contributory surrounding soil (unit cell) - fig. 5.

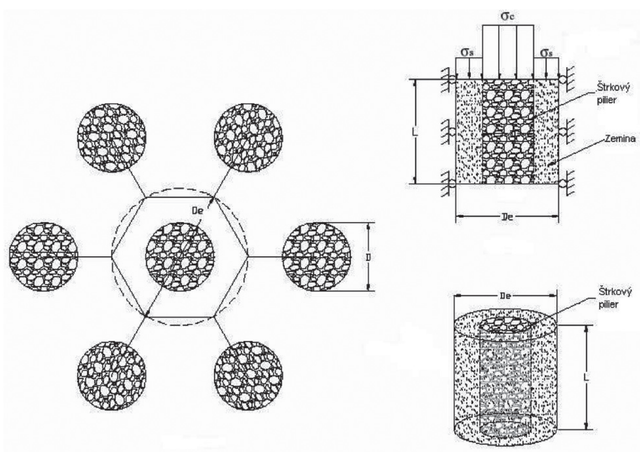

Fig. 5 *Unit cell (Barksdale,R.D.- Bachus,R.C. 1983) [2].*

Priebe assumes that this unit is surrounded by a rigid frictionless wall and that the vertical deformations are equal in every plane. He assumes that the column is stiff and uncompressible, whereas the surrounding soil is elastic. The stress distribution in the soil is isotropic, and a rigid base plate is above the stone column. Also, the load transferred to the subsurface soil is uniform.
For the analytical calculations the same soil properties as in the numerical and laboratory models were used. Table 6 shows the final soil improvement factor with the stone columns.

CONCLUSIONS

A comparison of all three approaches to estimate the soil improvement factor by the stone columns with Priebe´s original diagram is shown in fig. 6. The agreement of the results of the improvement factor calculated by Priebe`s method and, the FE method and obtained from the laboratory experiments appears satisfactory. All the models in this study were prepared by the vibro replacement method, which means that soil was removed out from the hole and not compacted to the sides such as in the vibro displacement method.

Acknowledgement:
This paper is part of the VEGA 1/0619/09 research program

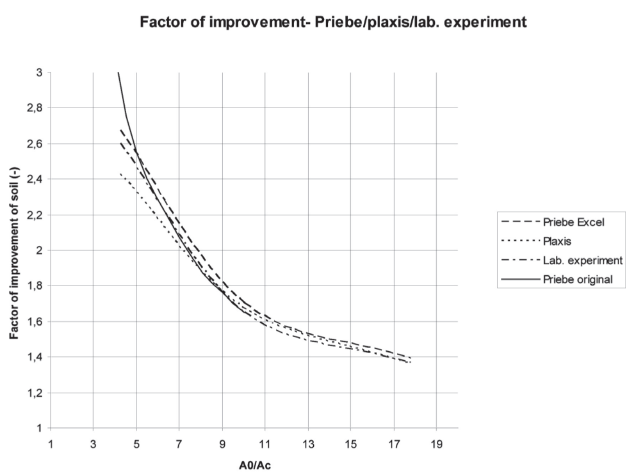

Fig. 6 *Comparison of the improvement factors calculated by the different approaches.*

SLOVAK JOURNAL OF CIVIL ENGINEERING

2011/3 PAGES 17 — 21

REFERENCES

[1] Hughes, J.M., Withers, N.J.: Reinforcing of soft cohesive soils with stone columns, 1974.
[2] Barksdale,R.D., Bachus,R.C.: Design and construction of stone columns, 1983.
[3] Mckelvey, D., Sivakumar, V., Bell, A., Graham, J.: Modelling vibrated stone columns in soft clay, 2004.
[4] Priebeh, J.: The Design of Vibro Replacement, 1995.