RESEARCH ON THE SHAPE OF STONE COLUMNS FORMED IN THE GROUND WITH THE USE OF DYNAMIC REPLACEMENT METHOD

Sławomir KWIECIEŃ [a], Jerzy SĘKOWSKI [b]

[a] Faculty of Civil Engineering, The Silesian University of Technology, Akademicka 5, 44-100 Gliwice, Poland
E-mail address: slawomir.kwiecien@polsl.pl

[b] Faculty of Civil Engineering, The Silesian University of Technology, Akademicka 5, 44-100 Gliwice, Poland
E-mail address: jerzy.sekowski@polsl.pl

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Abstract

The paper presents results of laboratory tests and site survey regarding shape of stone columns formed in the weak soils with the use of dynamic replacement method. The laboratory tests were carried out at specially constructed test stand, whereas the site survey was conducted on a few sections of currently constructed linear structures.

Streszczenie

W referacie przedstawione zostały wyniki badań laboratoryjnych i terenowych, nad kształtem kolumn kamiennych formowanych w gruncie słabym metodą wymiany dynamicznej. Badania laboratoryjne przeprowadzone zostały na specjalnie zbudowanym stanowisku badawczym, natomiast terenowe na kilku odcinkach realizowanych aktualnie obiektów liniowych.

Keywords: **Dynamic replacement; Stone columns; Tests on shape of the stone columns.**

1. INTRODUCTION

Driven stone columns are one of many methods used nowadays to strengthen weak subsoil [1]. Subsoil improved in this way increases its load capacity and rigidity, and columns mentioned above facilitate also its consolidation [2]. Literature body directly related to this method of strengthening weak subsoil is particularly modest.

Currently used engineering computational methods refer, because of their assumptions (cylindrical cross-section on the whole length), definitely more to columns constructed with the use of vibroreplacement method [3]. However, their use to determine load capacity and settlement of subsoil strengthened with the use of driven columns may raise serious doubts. The reason for such conclusion is a different method of forming driven columns. This insight is confirmed by observations and calculations made by first of the authors, included in the paper [4]. The shortest way of presenting them is as follows: settlements of individual columns measured for loadings similar to actual ones are clearly smaller than the ones calculated with the use of the above mentioned methods. It seams that to determine correctly settlements as well as load capacity of the subsoil strengthened with driven stone columns, knowledge of geometrical parameters of formed columns (column length and diameter) is required. Only tests connected with columns uncovering can clarify this issue. This was the reason for the idea of carrying out such tests, at first stage in laboratory and then followed by in situ. To carry out the first ones, adequate test stand was constructed.

The paper, after introducing columns production technology with the use of dynamic replacement method and above mentioned test stand, presents the results of laboratory and site tests regarding shape of columns constructed in this way.

2. METHOD OF STONE COLUMNS FORMATION

Machine enabling easy drop of heavy compactor from the specific height is used to insert stone material in the subsoil.

First, a crater is constructed by easy drop of the compactor and then it is filled with coarse material. Next the material is compacted with the use of the same compactor. Compaction lasts until resistance measured with compactor penetration per one drop exceeds distances determined in the design (usually around 5÷10 cm). Then partially filled crater is filled with another portion of material and procedure of column formation is repeated (Fig. 1a).

Construction of driven stone columns with machine called DYZAG [5] requires the use of compactor of shape similar to barrel (Fig. 1b) made of combined sheet metal plates. It is 1.97 m high with central diameter equal 1.05 m and top and bottom diameters equal 0.9 m. Mass amounting to 10.5 tons is dropped from the height up to 15 m. In our country we know also other types of the compactors used for consolidation or dynamic replacement (e.g. [6]).

Number of drops required to form a column varies from 7 to 15 times (depends on type of soil, blow energy). Diameter of columns formed in the above described way depends on soil susceptibility and may reach, in accordance with the design assumptions, even 1.7 m (the smallest diameter 1.2 m). The length of the column is established based on the geological-engineering documentation as well as quantity of material inserted in the subsoil.

Coarse material of diameter from 30 to 300 mm is usually used for columns construction. Despite virgin materials in the form of e.g. broken stone, various waste materials (e.g. burnt mining shale, blast furnace slag, waste stone, concrete debris) are now used more and more frequently.

3. LABORATORY TEST STAND

3.1. The stand construction

The stand constructional elements included (Fig. 2): steel posts „1" in the form of pair of welded channel bars as well as steel spandrel beam „2" (I 450) with regulated suspension. The stand construction was anchored in great forces plate. Columns formation took place in steel pipe „3" of 91.5 cm height and internal diameter 62 cm. Steel compactor „4" in the shape of barrel, of the size ten times smaller than the compactor used in machine DYZAG and of 10 kg mass was constructed for column formation. It was suspended with the use of line to the spandrel beam by permanent roller.

3.2. Materials

The following materials were used for modelling tests: medium sand of natural moisture content w_n=0.15% and vari-granularity index U=2.35, modelling base

Figure 1.
Driven stone columns: a) process of column formation; b) machine DYZAG 2 during construction of columns, with prototype compactor visible in the foreground

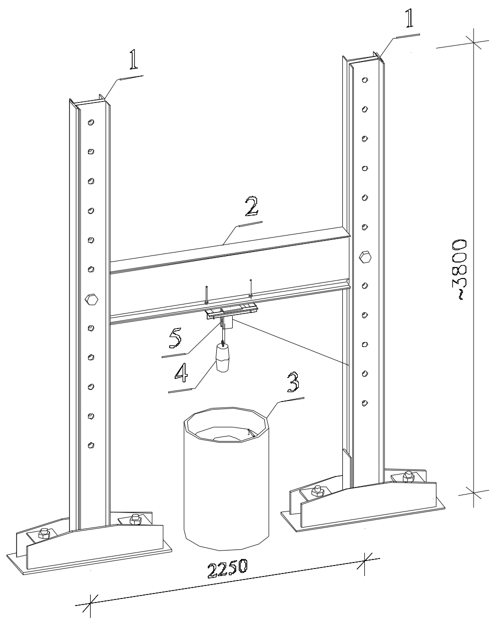

Figure 2.
Test stand for modelling tests

course in treated subsoil, peat of natural moisture content w_n=110% and organic parts content I_{om}=100% modelling weak layer as well as evenly-granulated (U=1.91) sharp-edged broken basalt of natural moisture content w_n=0.5% modelling a stone inclusion. The size of basalt fraction (4÷12 mm) was selected in such a way to be ten times smaller than fraction used in actual conditions. Base course thickness was 30 cm and it filled bottom part of testing chamber. The peat was laid on a sand layer.

3.3. Research programme and results

Laboratory tests included, among other things, determination of the stone columns shape formed with the use of the method presented in item 2. The following were employed in the tests as constant: kind and state of strong soil, kind of weak soils, stone inclusion material as well as mass and height of the compactor drop (h=1 m). Whereas, variables were the following: thickness and state of weak soil as well as conditions of strengthening construction. First columns set in 20, 40 and 60 cm thick peat loosely placed in testing chamber (columns no. 1, 2 and 3). Due to the fact that in practice columns are most often constructed from working platform (usually in the form of embankment layer), which enables operation of heavy equipment, in the second stage of tests such conditions were simulated by loading peat layer with 5 cm thick reinforced concrete slab of diameter 59 cm with internal opening of diameter 23 cm. Slab, giving unit pressure q=1 kPa, was applied right before column construction (no. 4). It needs to be added that thicknesses of weak layer and platform embankment (equivalent to load q), employed in particular tests, were originally ten times smaller than actual values. In the last test weak soil was preliminarily consolidated with load 6.5 kPa, whereas the column itself (no. 5) was constructed with simulation of working platform. All tested columns, right after forming, were filled with gypsum-water leaven of ratio 1/1 which facilitated their inventory control.

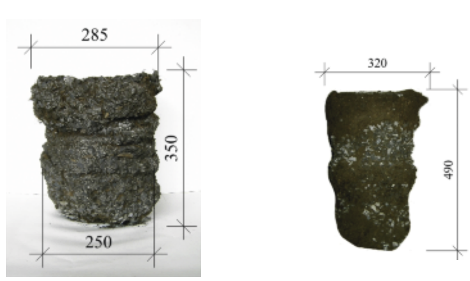

Figure 3.
Stone columns formed in the loose peat
a) of 40 cm thickness (no. 2), b) of 60 cm thickness (no. 3)

Figure 3a, b presents columns constructed in 40 and 60 cm thick loose peat. In case of these columns (lack of simulation of loading with the working platform) problems occurred in relation to formation of their heads. After dropping compactor from the height of

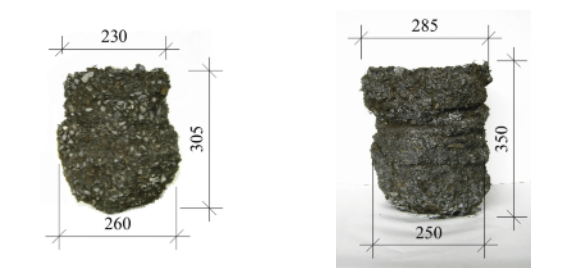

Figure 4.
Stone columns formed in 40 cm thick peat
a) with top load (simulation of working platform – no. 4),
b) without top load (no. 2)

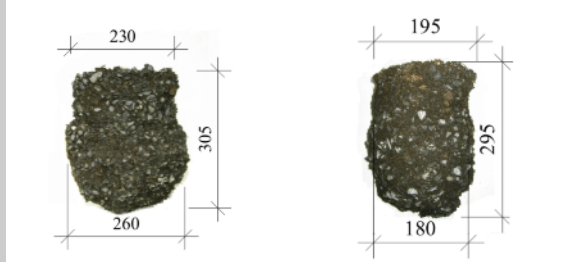

Figure 5.
Stone columns formed in 40 cm thick peat with simulation of working platform): a) without peat consolidation (no. 4), b) with peat consolidation (no. 5)

1 m material of column head was crushed asides, thank to which larger diameter was obtained than in the remaining part of the column. Additionally lifting of the peat surrounding the column under construction was observed.

With peat layer thicknesses, comparable with the compactor height, the column cross-section was constant on its length, whereas with bigger layer thicknesses it was changeable, with characteristic foot similar to half-moon (Fig. 3a and 3b).

Shapes of columns made in changing construction conditions (i.e. with working platform and without) are presented in Fig. 4. Practically only the top parts of these columns differ. The impact of loading with platform translates into decrease of heads diameter as well as its facilitated construction on the whole length.

In the last test column was formed in the consolidated peat with initial load of 6.5 kPa, with working platform simulation. Impact of weak soil susceptibility to column formed in this soil resulted in decrease of its diameter which is shown in Fig. 5.

Analysis of laboratory tests results forms the basis for the following comments:

1) columns constructed in laboratory conditions were chunky as the ratio of their length (H_k) to maximum diameter, measured in central section ($D_{k\,max}$), was smaller than 4 [7], practically not exceeding $K = \dfrac{H_k}{D_{k\,max}} = 2.2.$

2) ratio of column diameter in its central section ($D_{k\,max}$) to the employed compactor diameter (D_{ub}) - $\left(S = \dfrac{D_{k\,max}}{D_{ub}} \right)$ – for tested columns did not exceed 2.4 – smaller in case of little thickness of weak soil ($D_{k\,max} / D_{ub}$=1.8) and bigger in case of bigger thickness of weak soil as well as in case when this soil was more deformable($D_{k\,max} / D_{ub}$=2.4).

4. SITE TESTS

4.1. General characteristics of testing grounds

Testing grounds were located on two engineering structures under construction.

First of them was by-pass in Lubień near Myślenice on S-7 road, popularly called „Zakopianka". Section in chanage 710+145 ÷714+119 in northern part was running in Raba river valley. Base of the designed road embankments consisted of quaternary formations appearing in the surface layer in the form of aggregate mud of thickness reaching a few meters, divided with a layer of medium compacted gravels, under which there were layers of soft rocks in the form of sandstones and shales.

The second project was a construction of A1 motorway from Sośnica interchange (km 519+374.25) to Bełk interchange (km 534+785.39). Geologically the section was very complex. In the vast majority of the area, in the surface zone, there were organic soils in the form of aggregate mud and peat, soft-plastic cohesive soils as well as anthropogenic embankment soils of various thickness.

Geometry of total number of eleven columns, constructed with the use of dynamic replacement method, was tested in the above mentioned testing grounds.

4.2. Research on shape of the columns

All columns were formed with the use of about 0.5 m thick working platform enabling easy movement of heavy equipment. In case of particular projects constructed by different companies, dynamic replacement was performed with the use of equipment of similar blow energy (1.0÷1.68 MNm) and compactors of similar shape and sizes.

Inventory measurements of each column were performed, for safety reasons, from the ground level.

Ground-water conditions near and around each of the columns were determined based on the available geological-engineering documentation, revised by the authors with reference to thickness as well as kind and condition of weak soils in the cuts.

Dimensionless quantities S and K (item 3.3) introduced by the authors are used to describe particular columns.

Further part of the paper presents results of the conducted tests, illustrated by the selected graphic material.

First three columns (successively no. 1, 2 and 3) were constructed on road S-7 and made of crushed rock of fraction 0/400, in the square mesh of 3 m long side. They were formed in clayey aggregate mud of relatively small thickness (from 1 to 2 m). It had undoubtedly impact on the columns shape. They had similar overall dimensions, and the ratio of the column maximum diameter to the compactor diameter (S) ranged from 1.6 to 2.2. All columns were of the same length amounting to around 2 m, with slightly different heads diameters (1.6 m for column no. 1 to 2.2 m for column no. 3).

Test results including shape and geotechnical conditions for columns no. 1 and 3 have been presented in Fig. 6 (dimensions in the drawings provided in centimetres).

Next columns were constructed on the motorway A1, on four experimental plots (2 columns on each plot) located in the different spots of the above mentioned motorway.

Another pairs of columns (e.g. 4 and 5) were constructed in similar geotechnical conditions. The columns were constructed in equilateral triangle mesh of 3 m long side and blast furnace slug of fraction 30/120 was used for their formation.

First two columns (no. 4 and 5) were designed to strengthen layer of plastic clayey aggregate mud. Base course for columns consisted of medium compacted fine sand, providing bedding for weak soils.

Constructed columns did not reach base course floor and they were of similar length (successively 3 and 3.3 m). Their common feature was shape in the form of "a jar" widening downwards. However, they differed in dimensions, but had similar diameters ratio $D_{k\,max} / D_{ub}$ ($S = 1.9 \div 2.25$).

Pair of columns no. 6 and 7 was formed in different soil conditions. Both columns were footed on the base course and they were 4.2 m and 3.6 m long. Also in this case the columns were sort of "a jar" widening downwards. Shape of both columns was symmetrical. Ratio S amounted in this case to some 2.25.

Columns 8 and 9 presented in Fig. 7 were formed on the next experimental plot of the subsoil diversified geological structure. Non-constructional embankments and plastic cohesive soils constituted a weak zone. In both cases columns were 4 m long. Also here columns had characteristic shape of "a jar".

Quantity introduced by the authors was included in the range from 1.9 to 2.25.

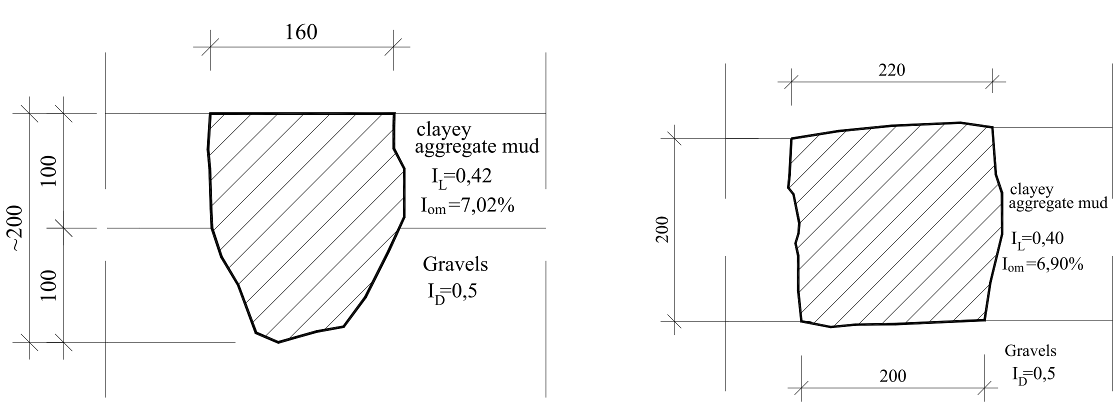

Figure 6.
Results of columns no. 1 (a) and no. 3 (b) inventory

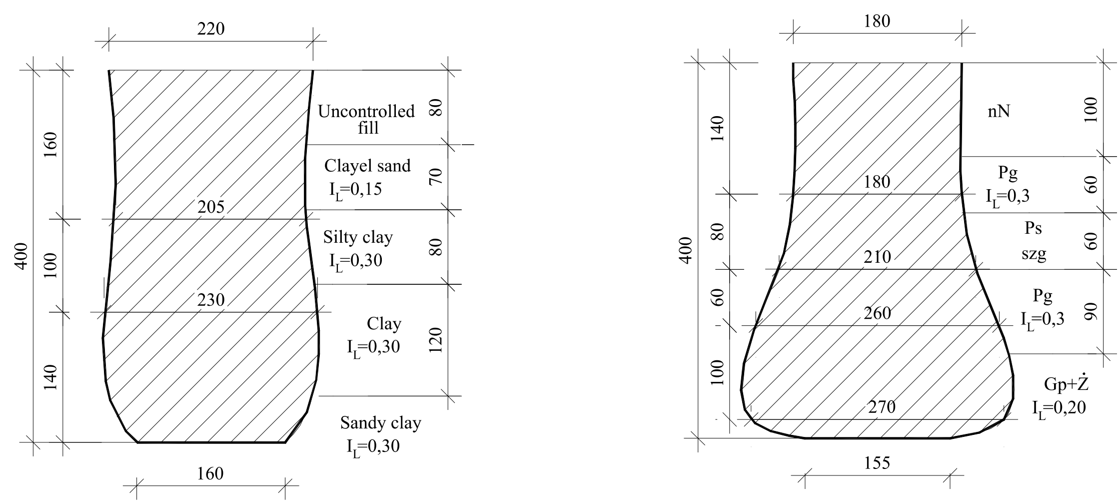

Figure 7.
Results of column no. 8 (a) and no. 9 (b) inventory

Next pair of columns (no. 10 and 11) was formed in homogeneous soil conditions. Base course consisted of plastic (I_L=0.3) cohesive soils of thickness over 5 m.

Formed columns slightly exceeded length of 4 m not reaching, at the same time, layer of hard-plastic dust. uite homogeneous soil conditions had effect on the shape of the formed columns different from the ones for which inventory was made before. The column had constant diameter on whole length with characteristically shaped base ("half-moon") – Fig. 8. Ratio S in both cases was on the level of around 1.6. Columns shape was symmetric.

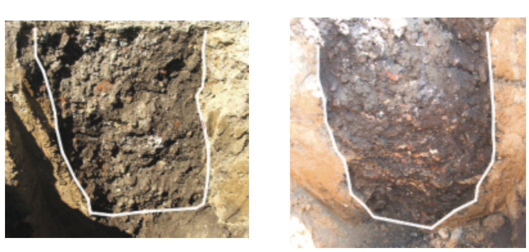

Figure 8.
Results of column no. 10 (a) and no. 11 (b) inventory

Summing up results of the conducted site tests, it needs to be stated that the columns had mostly changeable shape in length.

For short columns (no. 1, 2 and 3), for which weak layer thickness was smaller or equal to the compactor height, their diameter was practically constant. Similarly in case of longer columns (no. 10 and 11) formed in homogeneous layer of cohesive soils in plastic state.

In case of remaining columns formed in a few meters thick layered weak subsoil, they were of shape similar to "a jar" (e.g. Fig. 6). Small diameters of columns top part resulted from the use of working platform. For most of the columns, their base had "half-moon" shape. The ratio of columns height H_k to their selected diameters D_k (maximum and minimum) as well as the ratio of maximum diameter $D_{k\,max}$ to head diameter D_g have been listed in the Table no. 1.

According to the employed classification, columns formed in the weak subsoil were chunky $\left(\frac{H_k}{D_k} < 4\right)$ and ratio of their length to selected diameters (two first columns in Table 1) did not exceed the value of 2.8 fitting within the range from 0.9 to 2.8.

Analysis of the results included in the third column in the Table 1 shows that maximum diameter of columns formed in various conditions was bigger than diameter of their heads by maximum 80%, however, for most of them the ratio did not exceed 20%.

The ratio of maximum diameter of column to diameter of compactor introduced by the authors, did not exceed the value of 2.25.

Summing up the site tests it is possible to refer to laboratory tests. Shape of columns formed in very weak soils in site conditions (columns nos. 4 to 9) and in laboratory conditions (column no. 4) with working

Table 1.
List of introduced values characterizing columns

Column No.:	$\frac{H_k}{D_{k\,max}}$	$\frac{H_k}{D_{k\,min}}$	$\frac{H_k}{D_{k\,min}}$
1.	$\frac{2}{1.6}=1.25$	$\frac{2}{1.6}=1.25$	$\frac{1.6}{1.6}=1$
2.	$\frac{2}{2.2}=0.91$	$\frac{2}{2}=1$	$\frac{2.2}{2.2}=1$
3.	$\frac{2}{2.2}=0.91$	$\frac{2}{2}=1$	$\frac{2.2}{2}=1.1$
4.	$\frac{3}{2.7}=1.11$	$\frac{3}{1.8}=1.67$	$\frac{2.7}{1.9}=1.42$
5.	$\frac{3.3}{2}=1.65$	$\frac{3.3}{1.7}=1.94$	$\frac{2}{1.7}=1.18$
6.	$\frac{4.2}{2.7}=1.56$	$\frac{4.2}{1.5}=2.8$	$\frac{2.7}{1.5}=1.8$
7.	$\frac{3.6}{2.7}=1.33$	$\frac{3.6}{1.8}=2$	$\frac{2.7}{1.8}=1.5$
8.	$\frac{4}{2.3}=1.74$	$\frac{4}{2.05}=1.95$	$\frac{2.3}{2.2}=1.05$
9.	$\frac{4}{2.7}=1.48$	$\frac{4}{1.8}=2.2$	$\frac{2.7}{1.8}=1.5$
10.	$\frac{4.1}{1.8}=2.28$	$\frac{4.1}{1.6}=2.56$	$\frac{1.8}{1.7}=1.06$
11.	$\frac{4.0}{1.9}=2.11$	$\frac{4.0}{1.8}=2.22$	$\frac{1.9}{1.8}=1.06$

platform, corresponded in quality respect (shape of "a jar"). Quality similarity in shape respect was noted also in case of columns formed in site conditions (columns nos. 10 and 11) as well as laboratory ones (column no. 5) with the use of the working platform in less deformable soils (shape similar to cylindrical). At the same time, despite qualitative nature of the laboratory tests, obtained results were close to the results of tests conducted in natural scale.

5. SUMMARY

The paper has presented the results of laboratory and site research on the shape of stone columns formed in the weak soils with the use of the dynamic replacement method. Research conducted to date show that the shape is diversified. Shapes of columns depend, among other things, on the conditions they were formed in. In case of laboratory tests these were: thickness and consolidation degree of weak soil as well as method of columns construction (with and without working platform). However, in case of the site tests shapes of columns, when they were formed from the working platform, depended on kind and state of soils building the strengthened subsoil.

The columns diameters were bigger than diameter of the compactor forming them, in extreme cases even 2.5÷3 times bigger. It depended both on the weak subsoil rigidity and thickness as well as on method of columns formation.

Most of the columns did not have homogeneous cylindrical cross-section on the whole length. For them the characteristic were: column bottom similar in shape to "a half-moon", column bottom part in the shape of "a jar" as well as column head – widened or not in relation to diameter in the column middle part (depending on upper loading)

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