MODEL TESTS OF PHENOMENA OCCURRING DURING STONE COLUMN FORMATION

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Abstract

This paper discusses the results of model tests on the rammed stone columns shape and the soil deformations – as a consequence of soil strengthening. The tests description is preceded by information on the dynamic replacement method. The scientific research carried out so far focus on the final result of the strengthening, whereas the knowledge about the column formation process itself is insufficient. The model tests described in the paper are, according to the authors, one of the first attempts to examine the processes occurring in the soil during the driven stone column formation. The model tests were carried out in a rectangular box of dimensions 12x60x66 cm filled with sawdust. Three single columns were described. They were formed from granite aggregate in seven phases, with increasing ramming energy. The tests confirmed the barrel-like shape of the columns (from the beginning of the formation process), corresponding directly to the weak soil compaction. The research gave information on the ramming process efficiency on every stage of strengthening process and on the "cork effect" under the column. The conducted research form is the basis for further laboratory tests, performed with different boundary conditions. Their results may also serve to calibrate numerical model of the ramming process.

Streszczenie

W artykule omówiono wyniki badań modelowych nad kształtem wbijanych kolumn kamiennych oraz odkształceniami gruntu w następstwie wzmocnienia. Opis testów poprzedzono informacjami na temat metody wymiany dynamicznej. Prowadzone dotychczas badania naukowe skupiają się na efekcie końcowym wzmocnienia, natomiast brak jest wiedzy o samym procesie formowania kolumny. Opisane w artykule badania modelowe są jedną z pierwszych, zdaniem autorów, prób poznania zjawisk zachodzących w gruncie podczas wbijania kolumny kamiennej. Badania modelowe wykonano w płaskiej skrzyni o wymiarach 12x60x66 cm wypełnionej trocinami. Opisano trzy pojedyncze kolumny formowane z kruszywa granitowego w siedmiu etapach przy wzrastającej energii ubijania. Testy potwierdziły beczko podobny kształt kolumn (od początku formowania), z którym bezpośrednio koresponduje zagęszczenie gruntu słabego. Badania dały informacje na temat efektywności ubijania na poszczególnych etapach wzmocnienia oraz istnieniu zjawiska korka pod kolumną. Wykonane badania stanowią podstawę do dalszych testów laboratoryjnych przy innych warunkach brzegowych. Ich wyniki mogą również posłużyć do kalibracji modelu numerycznego procesu wbijania kolumny kamiennej.

Keywords: **Model tests; Dynamic replacement; Stone columns; Stone columns shape; Soil strengthening.**

1. INTRODUCTION

Buildings and engineering structures are more and more often located in the areas of unfavourable ground-water conditions. There are various methods of weak soil strengthening which can be alternative to deep foundation. One of them is the dynamic replacement method, developed in the 1980s [1] on the basis of dynamic consolidation.

Despite the increasing interest in the method, it was only in the recent years that its scientific development has progressed. The columns were uncovered in order to be inventoried. There were also attempts to load

the columns and to examine the subsoil consolidation around the columns, as well as propositions of dimensioning them [5]. The previous research focused on the final effect, however, the knowledge about the columns; behaviour during the formation process is still insufficient. This research aim was to advance the knowledge in this field.

In order to study the behaviour of the stone columns during the formation process, the authors planned a series of laboratory tests. The basis for the chosen methodology were relatively few research conducted by other authors (e.g. [5]), authors; preliminary test and intuition. The primary purpose of the qualitative research mentioned above is to determine the influence of the column formation process on its shape and on compaction of the soil around the column.

2. DYNAMIC REPLACEMENT METHOD

Dynamic replacement method is used to strengthen weak soil layers of thickness not exceeding 5.0-6.0 m. It allows the strengthening of very moist fine-grained soils with high content of fine fraction (clays and loams), weak organic soils and anthropogenic soils (e.g. landfills).

Dynamic replacement, called also driven stone columns, is based on constructing in subsoil columns of very high axial bearing capacity. The columns are formed by ramming with the use of a specially constructed rammer with the weight of 8-10 tons, dropped from the height of 10-30 m (Fig. 1). Shape and weight of the rammers and the impact height vary depending on the contractor [6].

The ramming process begins on the surface of the ground (Fig. 2a) or from working platform constructed previously (0.3-0.8 m thick working platform enables operations of heavy equipment on the surface of weak soil). The rammer impact drives the aggregate on the required depth, and then crater is filled up and the procedure is repeated (Fig. 2b). The number of impacts varies from 7 to 15 and depends on the kind, state and thickness of weak soil. The column construction is considered to be completed when the rammer does not continue driving into the ground.(Fig. 2c).

In result, we obtain strongly compacted column of diameter from 1.2 m to 4 m (Fig. 3), depending on soil type and applied formation technology. The stone column is described by the ratio of its length to the maxi-

Figure 1.
Exemplary equipment for dynamic replacement [6]

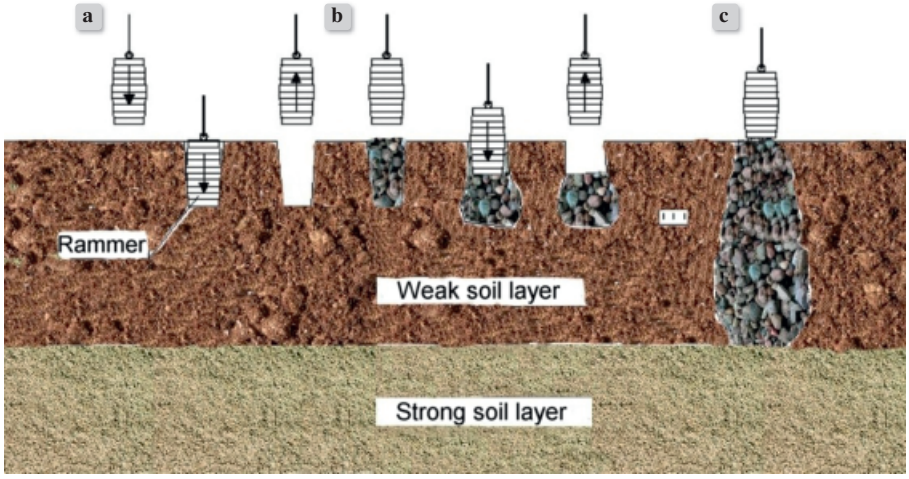

Figure 2.
Stone column formation process

mum diameter (H_k/D_{kmax}). In case of columns constructed with the dynamic replacement method, this value is almost always less than 4 – chunky column [2]. It is also possible to take into consideration the ratio of maximum column diameter to the used rammer diameter (D_{kmax}/D_u) [7]. The columns shapes can vary depending on the weak soil thickness, density index and the formation technology (choice of impact height, presence of working platform). However, generally the column is barrel-shaped with half-moon shaped base[7].

The columns influence also the soil near them. The ramming process induces an increase of pore pressure in the surrounding soil, what results in water filtration into the column, which acts like a drain. The column aggregate spreads asides, provoking shear strain of weak soil [1], what may be the cause of soil elevation near the column [6]. Mechanical properties of the soil are improved, its bearing capacity and stiffness increase.

Figure 3.
Column inventory [7]

Weak soil strengthening is the biggest in the direct proximity of the column, decreasing as the distance from the column grows. Soil strengthening between the columns is measured using e.g. the cone penetration test (CPT) before and after the dynamic replacement process. According to the research in 1:1 scale [8], the biggest horizontal displacement (soil density change) occurs slightly above the bottom of the weak layer, and the weak soil volume may decrease by many times as a result of the use of high impact energy.

Natural (rubble, aggregate material) and anthropogenic materials (slag, burnt shale) are used as column aggregate. The material should be vari-granular of fractions: 30/120, 30/300, 0/500 mm [5].

The distance between columns is chosen depending on load and type of construction that will be placed on the reinforced soil. In case of large structures, it is recommended to use regular distances in form of triangle, square [6] or hexagonal grid.

3. AUTHORS' LABORATORY TESTS

3.1. Test setup and material description

In order to conduct continuous observation of interaction between rammer, column and weak soil during the column formation process, the authors constructed test setup, which consists of (Fig. 4):

a) test box (12x60x66 cm). The front wall was made of

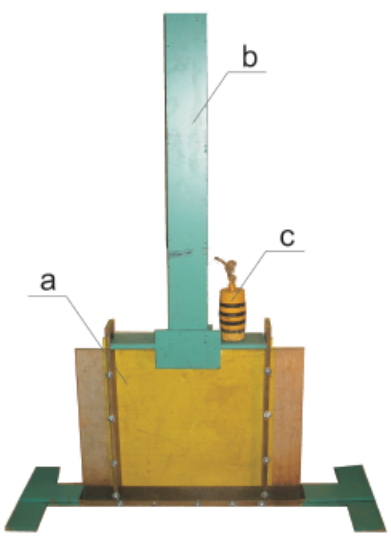

Figure 4.
Test setup

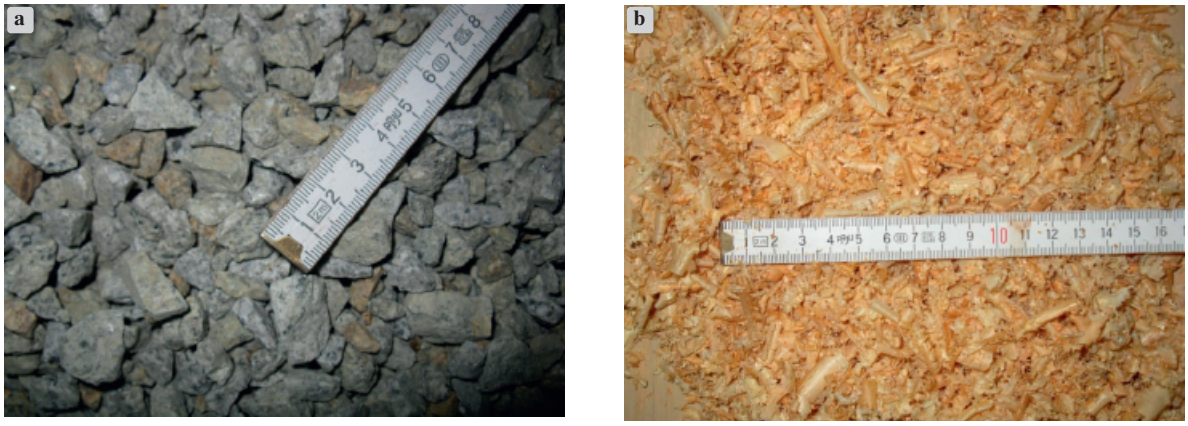

Figure 5.
Material representing: a) column aggregate – granite aggregate, b) weak soil – sawdust

acrylic glass, what enabled observation and photo documentation of the ramming process,

b) rammer channel of square cross section (12 cm x 12 cm) and 120 cm high. Its use eliminated the possibility of hitting the test setup walls by the falling compactor,

c) barrel-shaped rammer of 9 cm diameter in the bottom and top part, with the central diameter of D_u=10.5 cm. It was 20 cm high (H_u) and weighted 10 kg. The compactor used in the model test was ten times smaller than the real one [5] and its weight was over 1000 times smaller (10 kg/11.2 t).

The difference between the drop height in laboratory (h≈1 m) and in situ (H≈10 m), with the mentioned difference of their weight means that the energy obtained during the laboratory tests was over 10000 times smaller than the energy at building site. The energy obtained in the laboratory tests determined the use of soil weaker than it is in situ conditions. The soil was represented by sawdust, with graining (0.2÷3.0 cm) (Fig. 5b), whereas granite aggregate (granulation 0.5÷3.0 cm) (Fig. 5a) was selected to represent the column material, what reflected the actual conditions in 1:10 scale.

3.2. Research programme

Based on previous tests, the research procedure applied in formation of three columns made of granite aggregate was established.

The first column (No 1) was formed according to indications included in the paper [8] and after a few trial tests.

The formation technology was as follows:

– filling the test box with 53 cm high loosely placed sawdust – stage 0,
– creation of the crater – stage 1,
– ramming: stage 2 – filling the crater with aggregate, drop from the height of 10 cm,

Stage 3 – filling + 3 impacts (10 cm height)

Stage 4 – filling + 1x10 cm + 3x30 cm,

Stage 5 – filling + 1x30 cm + 1x50 cm+ 2x1 m,

Stage 6 – filling + 2x1 m + 1x1.2 m,

Stage 7 – filling + 4x1.2 m – end of the test.

The energy used for the columns formation has been shown on the bar chart below (Fig. 6). Column formation process was divided into 7 stages, separated by the action of filling the crater with aggregate.

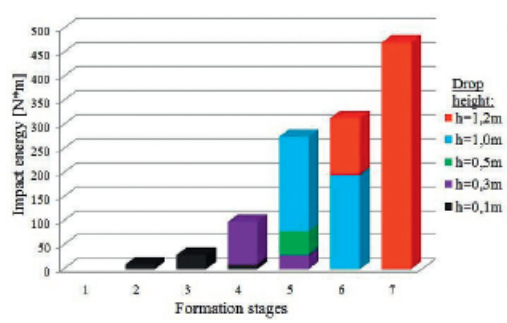

Figure 6.
Ramming energy combined with drop height

Paper straps, placed horizontally (one strap) and vertically (four others), were used to measure the weak soil strain, and, indirectly, the column shape. The method's correctness and the recurrence of the observations were verified for three columns (No 1÷3), formed in the way described above.

The case of column No 1, from stage "0" (the soil

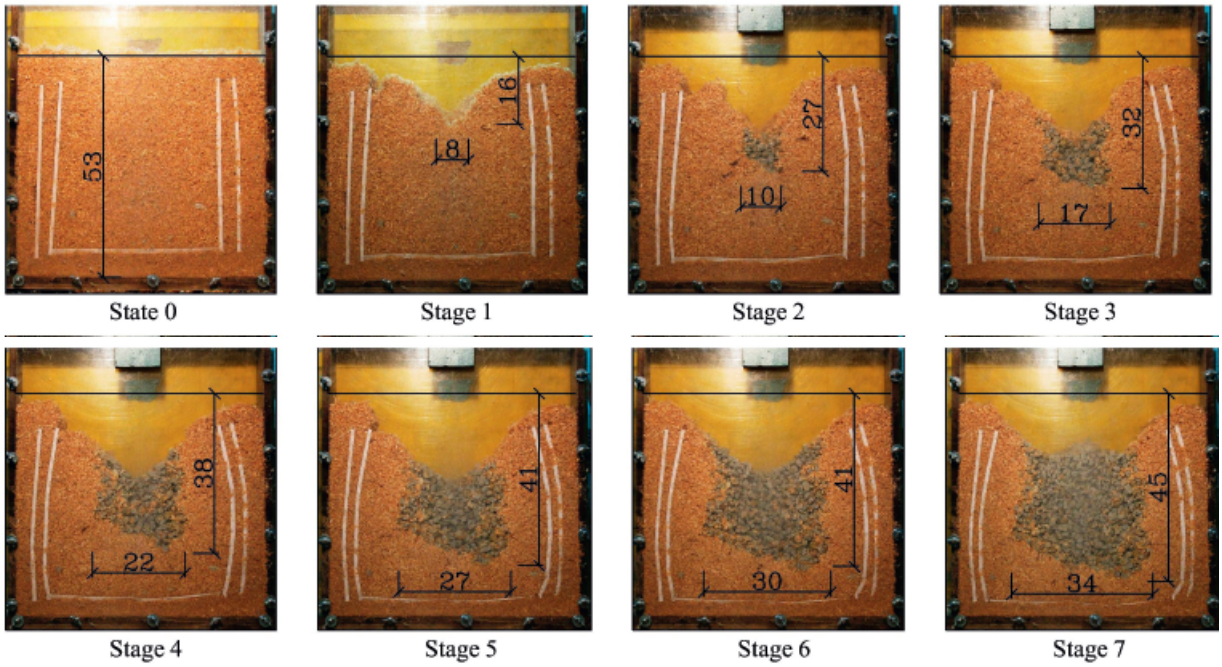

Figure 7.
Stages of column No. 1 formation

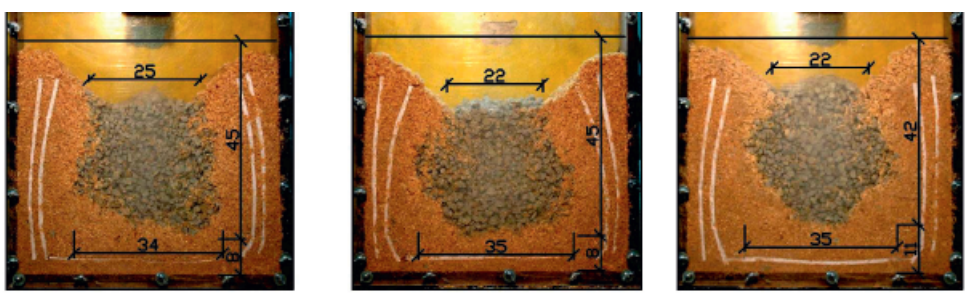

Figure 8.
Dimensions of columns no. 1, 2 and 3

before strengthening) and the column after each of the seven formation stages is presented in figure 7.

The results obtained for three columns are recurrent. At this stage of the test, barrel-like shape of the column was observed (Fig. 8), however, some local "bilateral perturbations" occur.

The columns lengths H_k (Fig. 8) were similar: 45, 45 and 42 cm (a bit larger than two lengths of the rammer). The columns were respectively 34, 35 and 35 cm wide (D_k) (which is over 3.5 times the rammer's diameter D_u). The ratio of the column's length to its width is for the analysed columns respectively 1.32; 1.29 and 1.20, which means that the formed columns were chunky ($H_k/D_k \leq 4$) [2].

The described columns are constructed as basic columns. The programme of conducted model test includes seven other column variations, constructed in different conditions:

- With simulation of working platform of small thickness (column No 4).
- With simulation of working platform of big thickness (column No 5).
- On weak soil compacted layer by layer (column No 6).

- With constant height of impact (column No 7) – small drop height.
- With constant height of impact (column No 8) – big drop height.
- After 30-days weak soil consolidation (column No 9).
- With weak soil thickness bigger than in case of the other tests (column No 10).

In this paper, only conclusions for basic columns were drawn. Full description of the research and the results are included in the paper [3], and some aspects in [4].

4. ANALYSIS OF MODEL TESTS RESULTS

The obtained results were considered in terms of column's shape analysis and the soil strengthening near it. These factors are interconnected and are essential also from the point of view of columns designer.

4.1. Columns shape

Column dimensions are undoubtedly one of its most important characteristics.

The tests were conducted in rectangular test box with their thickness much smaller than its other dimensions (plane strain). This approach, despite of some limitations, is an effective way to trace column shape changes during the formation process.

Each basic column was analysed in terms of their length and width change. Results characterising the mentioned values, described at the end of each formation stage, are the basis of the analysis.

After the end of ramming process, the space above the weak soil up to the ground level was not filled, but the analysed column was treated as if the filling was completed and column's length was measured from the original ground level.

In the examined conditions, after two first impacts the penetration constituted more than 50% of the final penetration depth. It proves that the soil in the initial stage is prone to load and, at the same time, indicates that the beginning of ramming is an important moment in column formation process. Following impacts did not show noticeable growth of column length until the increase of drop energy.

At the beginning of the column formation process bigger penetration depths than at the end were observed, despite increasing drop height of the rammer.

During the analysis, it was noticed that the column width increases at similar rate as during the entire formation process, however, after the first filling, the column achieves almost a half of the final value of the dimension in question.

It can be noticed (Fig. 9) that the column length and width during the entire ramming process were increasing practically in parallel. Two last stages are exception to this, what may prove smaller efficiency of ramming at the final stages of the test. Strengthening efficiency may be described during the observation of weak soil strain, which will be discussed in the following paragraph.

4.2. Weak soil compaction

Each of the formed columns was analysed considering soil strain near it. In this case, as well as in the

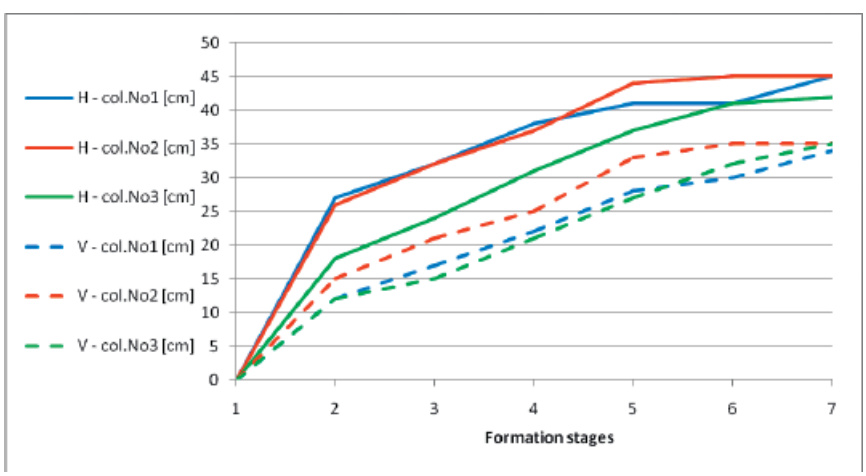

Figure 9.
The analysis of columns length (H) and width (V) change

description of the columns shape, the influence of the model setup dimensions (plane strain) on intensification of the sawdust density change was omitted.

In the conducted tests significant volume changes of weak soil around column was observed, as an effect of soil strengthening. It was noticed that the weak soil volume after the end of the ramming process was slightly over 50% of the initial volume, what may prove the improvement of weak soil properties. The mentioned change of weak soil volume concerns only the sawdust used in the test. It can be supposed that in other cases, the change will depend on weak soil Young's modulus, its strength and load history.

As it was mentioned above, through the entire process of column formation, parallel increase of its dimensions (length and width) was observed. It was the fastest at the beginning, and then it gradually decreased. It undoubtedly refers to the weak soil density change and its decreasing susceptibility to load. It should be noticed that it is contradictory to the ramming energy, increasing in the successive stages. To find out which influence dominates, the ramming energy (E_p) used to form columns at the successive stages of research was related to its length/width before and after each stage (H_k^i-H_k^{i-1} and V_k^i-V_k^{i-1}).

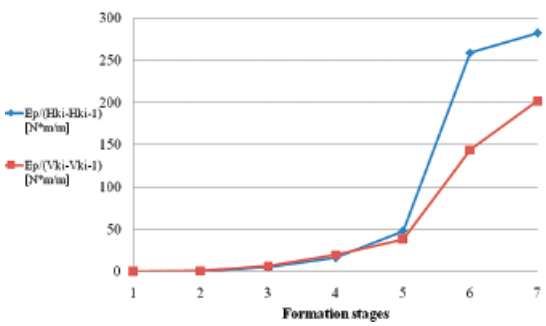

Figure 10.
The energy used for unit change of columns length/width

The results are presented in Fig. 10, which shows that every stage requires use of bigger energy to lengthen the column or extend its width of unit value. At the two last stages, when the column is almost formed, the value of the energy increases drastically.

It may turn out that the increase of energy in the final stages of column formation process is not an effective solution, apart from the expected strengthening of weak soil.

Besides the volume change of weak soil, its horizontal displacement was measured, by four paper straps placed in soil, two on each side of the column.

Figure 11 presents the weak soil compaction for each column, superimposing pictures of the test setup before and after ramming. It shows the straps in their initial and final position what enables the measure of their displacements directly from the picture.

The observed vertical straps displacement shows the shape similar to the column's shape (barrel-like), what allows to treat the weak soil displacement as a factor describing the column shape. Lateral strain, and hence the soil compaction level near the column, depends on its depth. There is an analogy to the depth of maximal lateral strain in relation to the column's length. In each case this value oscillates around the ratio of 0.8. On this basis it is possible to draw a thesis that there exists a constant depth on which the maximal soil density change occurs, resulting from horizontal displacements of the column's material.

The values of horizontal displacement depend on straps location. It can be noticed that the weak soil strain is smaller as the distance from the column increases. It determines the fact of bigger ground strengthening near the column. The results of internal straps displacements for one of the columns (no 1) were marked on the chart (Fig. 12).

Figure 11.
Straps deformation for columns number 1, 2, 3, after ramming

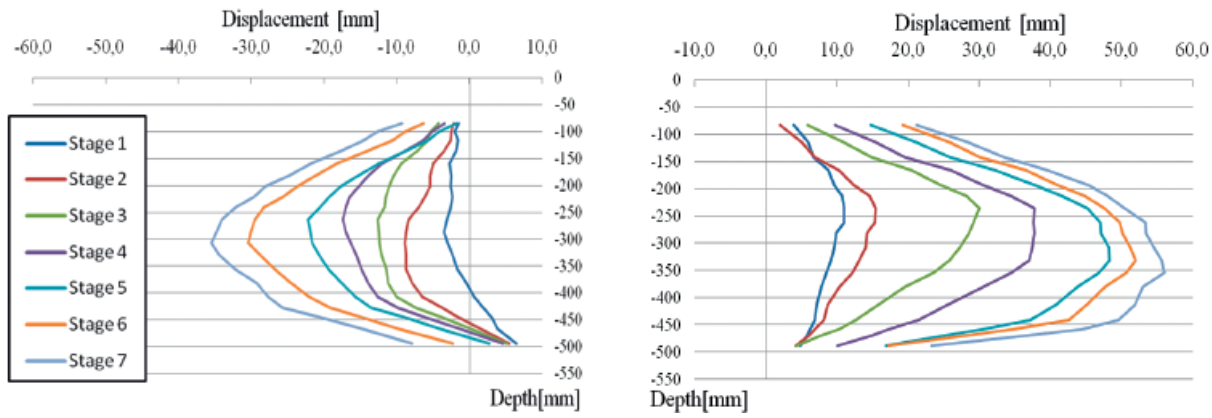

Figure 12.
Inner straps deformation in the soil near column No 1

The reference level on y-axis is the original soil level. The value "0" on x-axis marks straps position before the beginning of the process.

It can be noticed at first sight that the strain on the right side is about 50% bigger than on the left side. It would be affected by: asymmetric straps location, rammer impacts in different places (similarly to reality) or irregular column shape. As the method of driven column formation distinguishes itself by its simplicity, in consequence frequent irregularities and differences in columns shapes occur in reference to what could be supposed. In fact, asymmetric columns [5] are found.

A notable fact is that the barrel-like shape was formed after the first set of drops and was maintained till the end of the research. The displacements growths are in most cases similar. It should be noticed that displacement in both top and bottom parts are approximately similar.

What was interesting in all the studied cases was the behaviour of the strap situated under the column. It did not bulge on the column axis, as it could be supposed, but it settled evenly on its entire length. According to the authors, during ramming process, a lump of soil which settles evenly is formed. Its shape is showed in Fig. 13.

It is proved also by small lateral displacements at the bottom of the vertical straps (Fig. 12). They may as well result from straps continuity (straps strained in the top part pull the bottom), and not from the horizontal displacements of column aggregate on this depth.

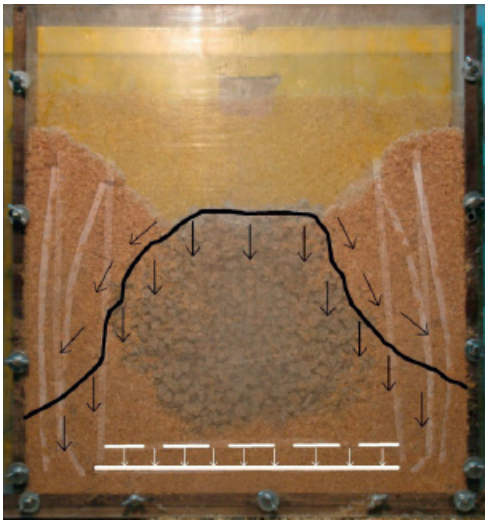

Figure 13.
Block of soil displacement

5. OBSERVATIONS

Despite of their qualitative character, the results of the conducted research are the basis for the following observations:

- Strong compaction of weak soil appears under the column, in the form of so-called "cork".
- Assuming constant ground level, volume of weak soil may decrease considerably, what proves its compaction and strengthening.
- Barrel-like shape of the column is obtained already after the first drops set and is maintained till the end of ramming process.
- Soil consolidation near the column depends on the distance from the column and on the depth. Maximal compaction occurs on the depth of about 0.8 of the column.

- During the column formation, a block of soil is created and settles evenly.
- The energy required to enlarge the column in the final formation stage is a few times bigger than the energy required in the initial stages.

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