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FIELD TEST OF DEFORMATION OCCURRING IN THE SURROUNDINGS OF A RAMMED STONE COLUMN

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Abstract

This paper discusses the results of field tests which focused on deformation phenomena occurring in the surrounding of rammed stone column. The basic device used to perform the tests were inclinometers installed at different distances from the formed stone column. Not only the data obtained during inclinometer measurements were collected, but also additional data from ground uplift investigations, column excavation and the authors' observations. Each part of the paper presents firstly some general information on the subject in question and then the details concerning test field investigations.

Streszczenie

W artykule omówiono wyniki badań polowych skupiających się na poznaniu zjawisk deformacyjnych zachodzących w otoczeniu wbijanej kolumny kamiennej. Zasadniczymi narzędziami służącymi do wykonania testów były inklinometry zainstalowane w różnej odległości od formowanej kolumny kamiennej. Uzyskane za ich pośrednictwem wyniki uzupełnione zostały informacjami z badań wypiętrzeń gruntu, odkrywki kolumny oraz obserwacjami autorów. W poszczególnych częściach artykułu podano najpierw informacje ogólne, a następnie dane szczegółowe, odnoszące się do poletka badawczego.

Keywords: **Dynamic replacement; Stone columns; Soil deformation; In situ tests; Soil strengthening.**

1. INTRODUCTION

Nowadays, there is a great interest in geoengineering, due, among others, to the shortage of areas unquestionably appropriate for the foundation of buildings. Within the scope of geoengineering, numerous methods of weak soil improvement have been developed. In Poland, they have been classified e.g. by Gryczmański [3].

One of the methods of soil improvement willingly applied nowadays is dynamic replacement. The method is very simple, quick and consequently – inexpensive. Although the mechanisms occurring during soil improvement do not seem to be complicated, they have not been fully identified until now. The developed theories and performed observations do not provide any complete analytical solution. The occurring strengthening mechanisms seem to be complicated and difficult to describe from the theoretical point of view. The main drawback of dynamic replacement method is the absence of design algorithms that would permit to predict the results of soil improvement. From this point of view, the authors have for a few years been conducting research and analyses of soil improvement with the dynamic replacement method.

Currently, the focus of the research is to identify the influence of stone column formation process on the surrounding soil. The aim of the *in situ* investigations described in this paper, was, among others, to learn more about deformations occurring during column formation process. The authors described as follows: soil volume change due to ground improvement, horizontal displacements of subsoil and ground uplifts. The largest part of the article is dedicated to inclinometer measurements from which most of the data were obtained.

Field investigations were performed on 14 m x 14 m test field located in south-eastern part of Poland, in the direct proximity of a thoroughfare under construction. The location was chosen due to its ground conditions, which were determined on the basis of cone penetration tests (CPT) performed for the investment.

2. SOIL CONDITIONS

The dynamic replacement method allows to improve weak soil up to the depth of 6 meters. It can be applied to improve the strength of very moist cohesive soils, as well as anthropogenic and organic soils. The depth limit results from the technology itself. Considering the weight of the used rammers and drop height, the formation of longer columns is impossible from technical point of view. The columns length reaches up to several meters and further drops widen the column but have no impact on its length. In cohesive soils, there is a probability that after introducing the rammer at the depth of several meters, it would be impossible to pull it out of the hole due to suction forces. For bigger depths, stone columns can be applied together with other methods, like e. g. microblasting [7].

In the area where the experimental investigations were conducted, CPTU and DMT penetration tests, as well as mechanical drilling, had been performed in order to identify soil conditions. CPTU and DMT penetration tests were conducted up to the depth of 6 meters, and the drilling – up to 7.5 meters below ground level. The investigations and analyses [20] have shown that the subsoil is composed of four specific soil zones (Fig. 1):

I. The first layer, reaching up to about 1.5 m is composed of medium dense silty sands and sandy silt, classified as soft/firm.

II. The second layer, located between 1.5 m and 2.5 m below ground level is composed of soft and very soft silty deposits.

III. The third layer, which occurs up to 4.8 m consists of soft silty deposits with higher content of loose and medium dense sandy soils.

IV. The fourth, underlying layer is formed of medium dense fine sands and medium dense medium sands. These sands make the bearing layer.

The drillings allowed to determine on what level ground water occurred. The water table met during drilling was found at the depth of 5.3 m below ground level and the stabilized water table occurred at the depth of 3.0 m below ground level (Fig. 1).

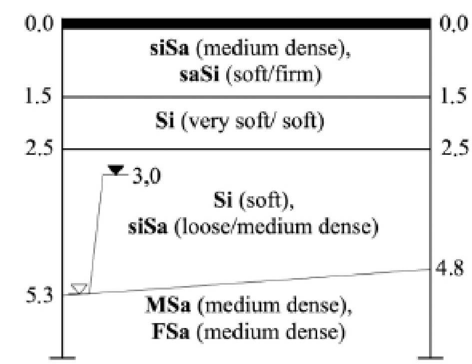

Figure 1.
Soil conditions on the test field

3. INCLINOMETERS

3.1. The methodology of inclinometer measurements

Inclinometer measurements are conducted using a set of measuring elements which consists of:

– guide casings made of ABS plastic (Fig. 2b) or of aluminium,

– inclinometer probe (Fig. 2a),

– data acquisition unit,

– caps (Fig. 2a) protecting guide casings from accidental damage [14].

Guide casings diameters can vary depending on the manufacturer (e.g. 48, 70 or 85 mm [14]), who also defines the length of casings, e.g. 3 m. Longer casings are obtained by connecting shorter elements. The lower part of the guide casing is ended with a special bottom cap.

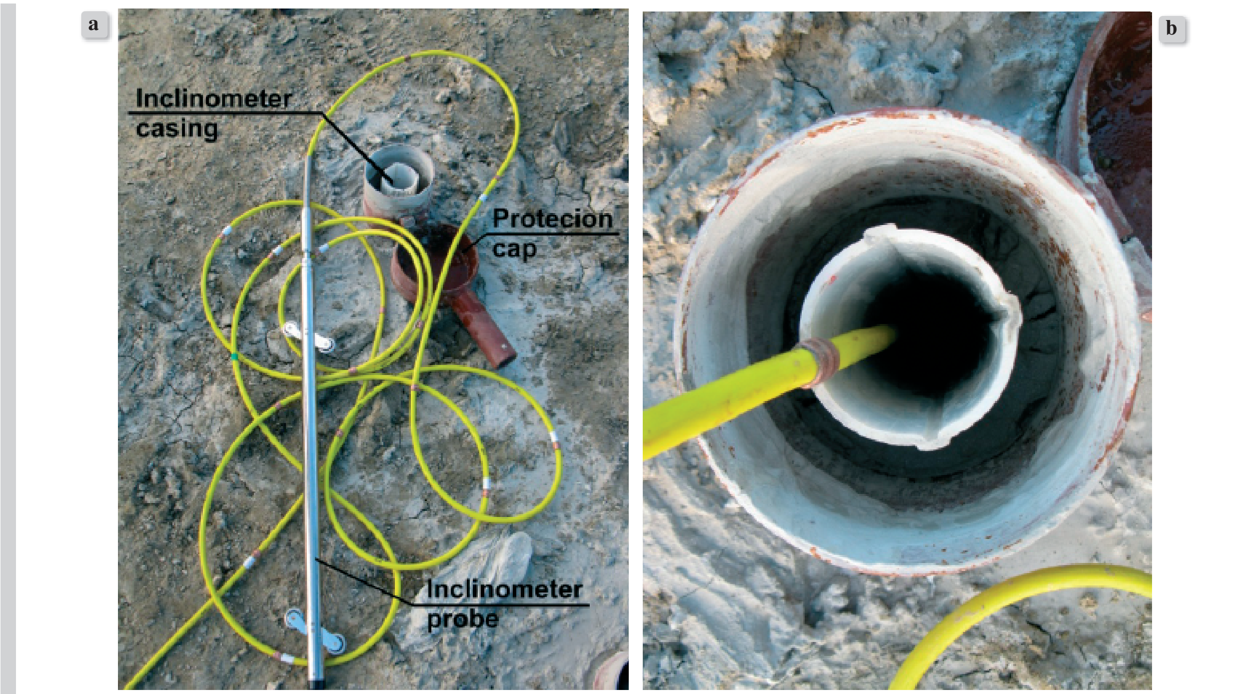

Figure 2.
Set for inclinometer measurements: a) guide casing, cap, probe; b) guide casing details

Guide casings are introduced into boreholes. The borehole diameter needs to be larger than the casing outer diameter. Drilling can be performed in the piping and guide casings should be inserted into the boreholes as soon as possible. The space between the casing and the borehole should be filled with mixture on the basis of cement and bentonite. If the installation is hindered by buoyancy, the inclinometer casing should be weighed or filled with water. Then it should be left for at least seven days to allow the cement mixture to harden.

After that time, guide casings patency is checked and so-called zero measurement is performed to determine the initial position of casings. Subsequent measurements are performed according to the adopted research methodology.

Horizontal displacements are not determined directly by inclinometers, but on the basis of the measured probe inclination from the vertical axis verified in every measuring section. Inclinometers customarily are equipped with tilt sensors, which allows to detect inclinations in two directions. The probe can be guided in casings due to grooves of the casings spaced 90° apart (Fig. 2b). Following the standard procedures, four measurements are performed, after each of them the probe is rotated 90°. The third measurement is a control measurement for the first one, whereas the fourth – for the second one. The inclinometer probe is lowered to the bottom of the guide casing where it registers the data. Then, as the probe is being pulled up, the readings of its inclination from vertical are taken at every 0.5 m or 1.0 m intervals [14] until the probe is taken out from the soil. On the basis of the obtained tilt data, vertical displacement is calculated by the data acquisition device. The results can be read immediately after the measurement.

3.2. Scope of application

Inclinometer measurements are the most frequently applied in landslides monitoring [19], [21] in order to determine subsoil displacement. They are also used for slopes [1], slurry walls [22], retaining walls and deep excavations measurements. Moreover, the inclinometers are applied to monitor piles which are exposed to great horizontal strength, as well as to monitor embankment settlements, road surface deformations and soil displacements during tunnel formation [14]. On the areas influenced by the mining exploitation, inclinometer measurements are used to determine repeatedly changing rock mass displacements [21].

The use of inclinometers for measuring the influence of stone column formation process on the surrounding soil can be considered as a non-standard use.

Besides research described in this paper, inclinometer measurements were used to determine the deformation of soil improved with dynamic replacement method on test field located in the USA [18].

There is an innovative solution in which casings imitating inclinometer casings are used in laboratory tests. To imitate inclinometer casings, the authors of the article used soft cable covers whose diameter was 3 mm, installed in the surrounding of a formed stone column in 1:40 scale. Cable covers were filled with plaster. The principle of the measurement was to excavate cable covers imitating inclinometer casings and to verify their displacement (Fig. 3).

Figure 3.
Measurements imitating inclinometer casings in laboratory conditions

3.3. Investigation methodology on the test field

The specificity of dynamic replacement method, which results in soil displacements around the column, corresponds well with inclinometer measurements. The data on soil displacement around the stone column during its formation process and exploitation can be easily and quickly obtained due to inclinometers located in the appropriate places.

Inclinometers were installed on the test field two weeks prior to column formation. Two holes of the diameter of 150 mm were drilled using drilling rig H25SG. 71 mm diameter inclinometer casings made of ABS plastic were introduced into the boreholes. Each casing consisted of three sections connected with couplings which were screw-tightened to both connected parts of the casing. The coupling was sealed with silicone and wrapped with special self-sealing tape. The space between the inclinometer casing and the hole was filled with ground-cement mixture and then left for two weeks in order to allow the mixture to harden. The casing bottom was closed with cork and the upper part was protected with steel pipe cover.

There were six 7.5-meter long inclinometers installed on the test field. Figure 4 shows columns location scheme and columns marking.

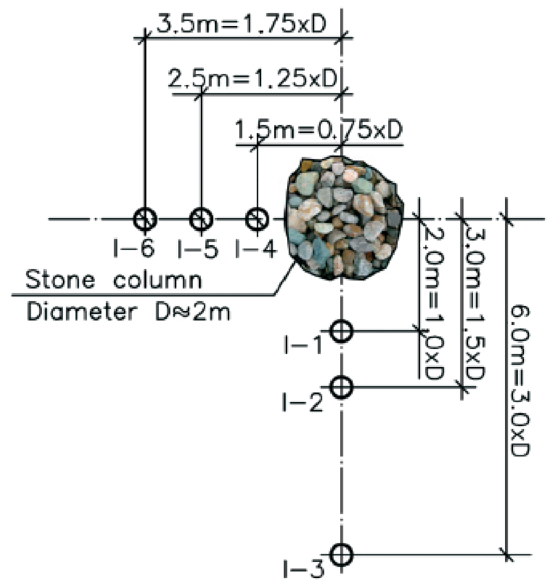

Figure 4.
Location scheme of inclinometers

Five sets of measurements were performed for each inclinometer casing. The first set was conducted before ramming process, the following three after each column formation stage and the last one – 30 days after column formation was completed.

According to the standard procedures, four measurements were performed in every set and after each of them the probe was rotated 90°. The probe tilt was registered at 0.5 m intervals, up to the moment when it was pulled out. The obtained data were used to calculate horizontal displacement (firstly using the software and secondly – verified in spreadsheet).

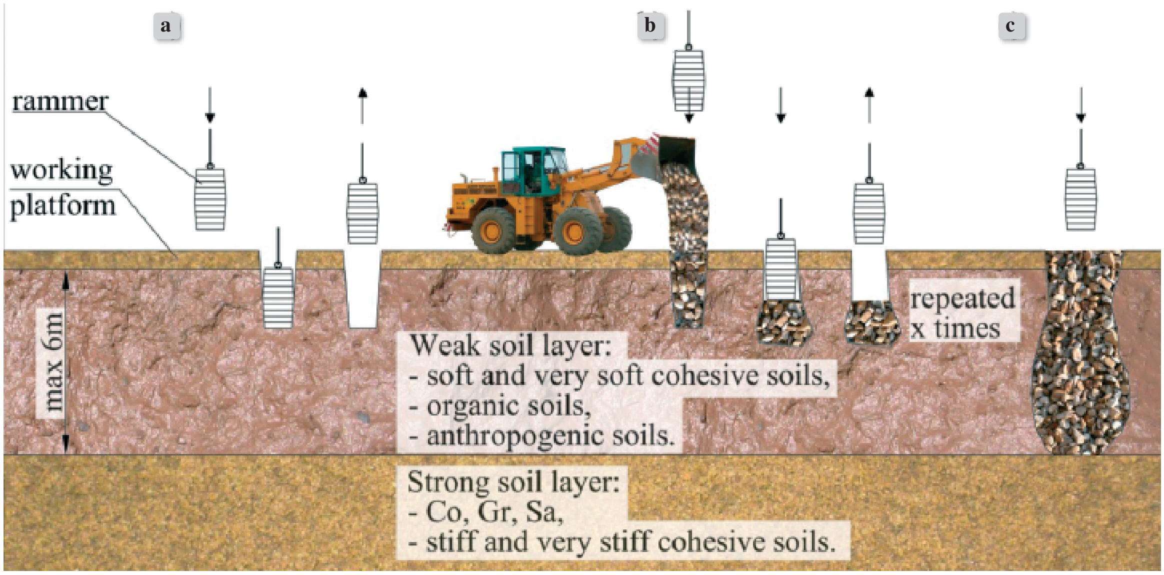

Figure 5.
Stone column formation process

4. STONE COLUMN FORMATION IN THE DYNAMIC REPLACEMENT METHOD

4.1. General information

In dynamic replacement method, also known as driven stone columns, columns made of stone of high axial bearing capacity are formed in soil. In Poland, the rammer used in column formation weighs 8 to 20 tons and is dropped from up to 25 m. Shape and weight of rammers, as well as the drop height, vary and depend on the contractor [17]. The ramming process starts on the surface of the ground or on the previously constructed working platform. The platform, which is 0.3-0.8 m thick enables the use of heavy equipment on the surface of weak soil. After the first drop of the rammer a crater is formed and the following drops press the aggregate on the required depth. The rammer is then pulled out of the hole, the crater is refilled and the procedure is repeated. The number of drops varies depending on the contractor, as well as on weak soil type, state and thickness. The number of drops needed to form the column on a given building site can be determined on a test field. The column formation is considered to be completed when the depth on which the dropping rammer is introduced is very low (0.1-0.2 m). Figure 5 shows the stages of column formation in dynamic replacement method.

The following material are used as the column aggregate: rubble, stone aggregate, blastfurnace slag, burnt shale and debris. It is important that the aggregate is not destroyed during column formation. To ensure high stiffness of columns, the aggregate should consist of materials of various fractions (30/120, 30/300, 0/500 mm) [12].

Depending on loading and on the type of construction that will be founded on the strengthened soil, column spacing is chosen. In case of big surface structures, regular spacing in form of triangle, square and hexagonal [2] grid is recommended.

4.2. Column formation on test field

The stone column was formed with the use of equipment which enabled the drop of the 11-tons barrel-like rammer from the height of 15 m (Fig. 6). The rammer was 1.65 m height and its maximal diameter was D = 1.0 m. The column was made of the mixture (1:1 proportion) of fine gravel with coarse sand and rubble of 0-200 mm fraction.

36 drops from different heights were needed to form the column. The backfill volume was 1.1 or 2.2 m^3 of loose soil, whereas 20.9 m^3 of loose aggregate was used to form the column. Figure 7 shows drop heights and backfill volume, as well as crater depth verified after each drop.

Column formation was divided into three series of drops. Drops 1-9 constituted the first series, drops 10-23 – the second one and drops 24-36 were performed in the third series. During column formation, ground uplift adjacent to the column crater was

Figure 6.
Crane during column formation

observed, as well as the cracking of the ground (Fig. 8). In the proximity of the inclinometer placed at the closest distance to the column, the first crackings appeared already during crater formation.

5. STONE COLUMN SHAPE

5.1. General information

As the result of dynamic replacement, a stone column of high density is formed. The column diameter varies from 1.2 to 4.1m [13], depending on soil type and the applied technology. The maximal column length is approximately 5 m [13]. For several years, two of the co-authors (Sękowski, Kwiecień) have led the research on the shapes of rammed stone columns. The research allowed to determine the influence of ground-water conditions on the shape of formed columns [13]. There is much less information on the influence of the applied technology. The only existing observations in Poland have been made during laboratory tests (Kwiecień, Kanty) in which various drop energies of the rammer were applied [8], [9].

Stone column is described by the ratio of its length to its maximal diameter (H_k/D_{kmax}). For columns constructed with the dynamic replacement method, this value is almost always less than 4 [13]. In this case, the column is described as chunky [6].

The columns influence also the weak soil near them. The ramming process results in the increase of pore pressure in the surrounding soil, soil deformations and changes of soil strength and strain parameters [4].

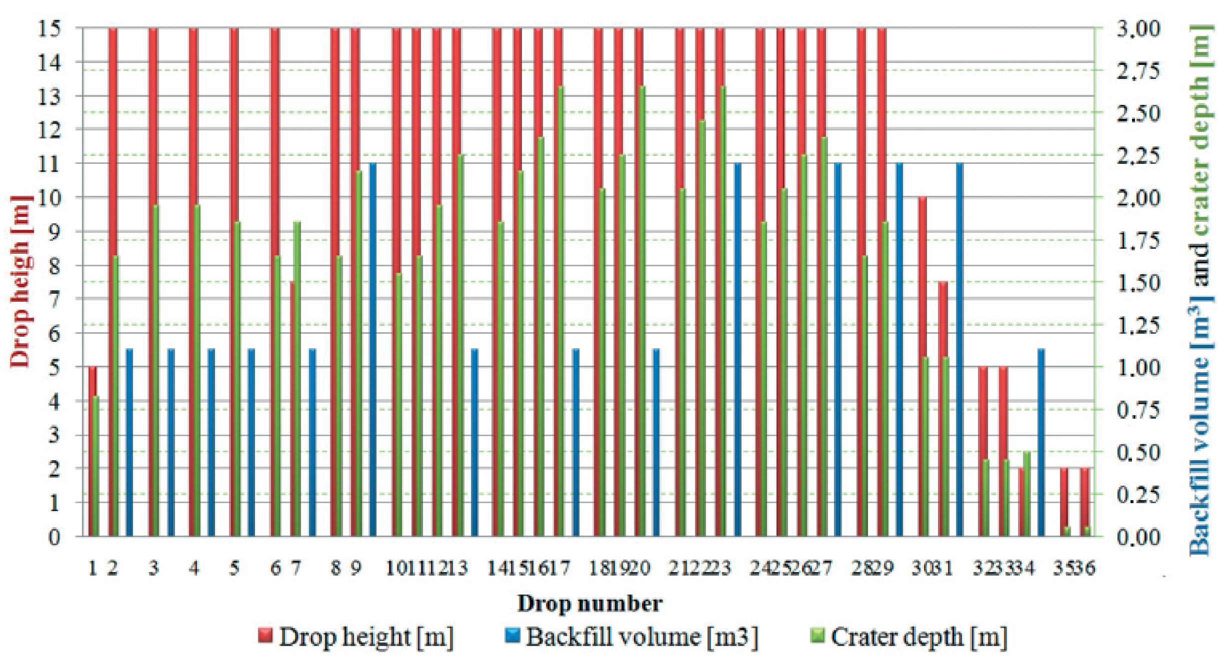

Figure 7.
Drop height, rammer penetration and backfill volume during field tests

Figure 8.
Ground cracking near the crater

5.2. On the test field

The diameter of column head, inventoried when column formation process was completed, was 2.0 m. Column diameter verified after column excavation was 1.9 m. The maximal diameter measured during the excavation was 2.8 m and the column's length was 3.8 m (Fig. 9).

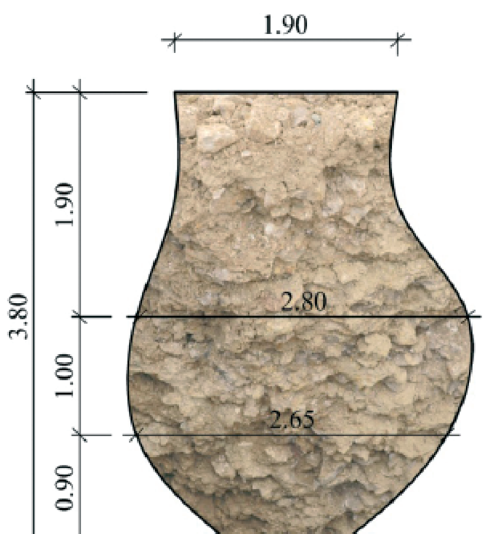

Figure 9.
Inventoried column dimensions [m]

Assuming that the column is symmetric, the backfill volume can be estimated at 16.1 m³.

6. GROUND UPLIFT ADJACENT TO THE RAMMED STONE COLUMN

6.1. General information

When dynamic replacement method is performed, ground uplift is usually not measured. In turn, the measurement of the rammer penetration depth (crater depth) is conducted [6]. Ground uplift is measured in soil strengthening by dynamic consolidation method [15] and e. g. during driving of prefabricated piles [5].

The results of the authors' research on ground uplift around stone column are presented in papers [10] and [11].

6.2. Investigations on the test field

Investigations conducted on the test field completed the basic measurements. It was acknowledged that the horizontal displacement measured with inclinometers are accompanied by vertical displacements. Ground uplift measurements were performed in 7 points located at 2 to 6 meters from the column axis. The change of uplift height was verified after each series of drops during column formation process. Figure 10 shows the results of the measurements. The distance between the measurement point and the column axis (r) divided by rammer diameter (d) is presented on the x axis.

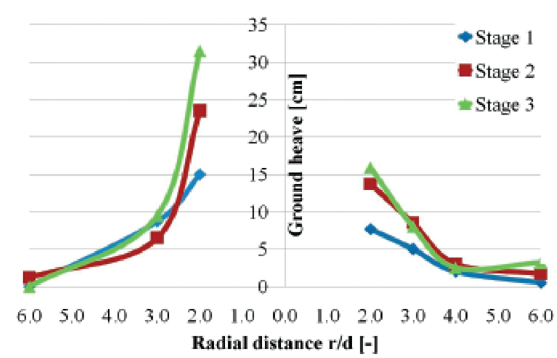

Figure 10.
Ground uplift near the column

The points where ground uplift was measured were placed in one line. However, the most asymmetrical values at both sides of the column were recorded in the points located at the closest distance from the column. The difference in the uplift is up to 200%. In points located at a distance of at least 3 m no asymmetry was observed. It was estimated that the uplift appeared in the radius of 6 m from the column. At this distance, uplift values were close to measurement error. Further observations concerning the data collected during uplift measurements, as well as the horizontal displacement data, are presented in the following chapter.

7. INCLINOMETER TESTS RESULTS

After the first stage of column formation, the measurement inside I-4 (Fig. 4) casing was impossible due to significant deformation. At the second stage, water appeared inside the casing, what may lead to the conclusion that the casing continuity was interrupted and the casing was destroyed. Similar behavior was observed for inclinometer casing I-1. The difference was that after the first ramming series it was possible to perform the reading of horizontal displacement. During the second formation stage, the inclinometer casing was obstructed. At the third stage, water appeared inside the casing. I-4 casing displacement is not presented in the following chapter due to the destruction of the casing. For I-1 casing, only the data from the first stage of column formation is shown.

Displacement values for two perpedicular inclinometers are shown in figures 11 and 12. The initial observation is that in both measurement axes there is no symmetry in inclinometer deformation. I-2 inclinometer (3.0 m from the column axis) indicated larger deflection than inclinometers I-5 and I-6 (located respectively at 2.5 m and 3.5 m from the column axis). The maximal terminal values of horizontal deformations vary by up to 300% (I-2: 5.6 cm; I-5: 17.0 cm; I-6: 13.6 cm). This tendency is visible already on the first stage of column formation. The asymmetry may result from the fact that during the formation process, column aggregate does not spread symmetrically. After being introduced into the ground, the aggregate usually tilted in the axis of inclinometers I-5 and I-6. The base center of the rammer hitting the ground could have been some ten to twenty centimeters from the intersection of inclinometer axes.

On the basis of the measurements, the radius of the influence of column formation process was determined to be more than 6 m (6D – six times the rammer diameter), measuring from the column axis. The inclinometer placed at this distance indicated regular displacements exceeding the measuring error whose maximal value was 1.2 cm.

The analysis of the measurement data shows that the

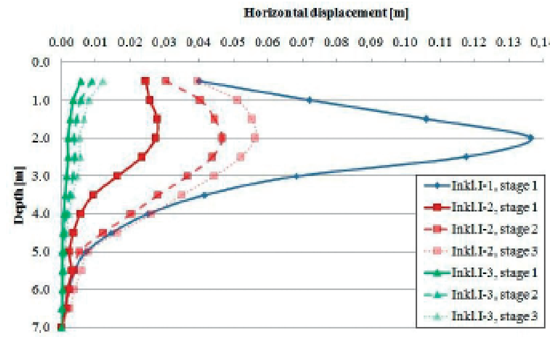

Figure 11.
Horizontal displacements for I-1, I-2 and I-3 inclinometers

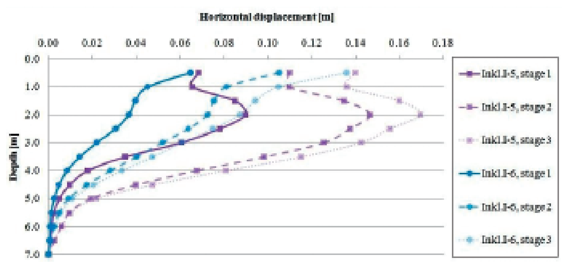

Figure 12.
Horizontal displacements for I-5 and I-6 inclinometers

displacements of I-1, I-2 and I-5 inclinometers (located at the closest distance from the column) have different character than the displacements of I-3 and I-6 inclinometers, located the farthest from the column. The maximal ground displacement near the column was identified at the depth of 2 m, which is true for every stage of the investigation. It corresponds with the column shape determined during excavation, as that was the approximate depth at which the maximal column diameter was recognized (Fig. 9). The maximal displacements measured by the inclinometers located at the farthest distance from the stone column were measured close to the soil surface. Slightly bigger displacements can be observed at the depth of 2 m. However, these are not the maximal values measured for a given inclinometer casing. According to the authors, it can be caused by different character of surface and body waves propagation. Surface waves influence larger area than body waves, whereas the latter provoke more significant displacements in the proximity of the column and fade away more quickly.

The last inclinometer readings were performed 30 days after column formation and after trial loading. Soil movement towards the column was measured for all inclinometers. The maximal soil displacement in this direction was 7 mm. The influence of trial load-

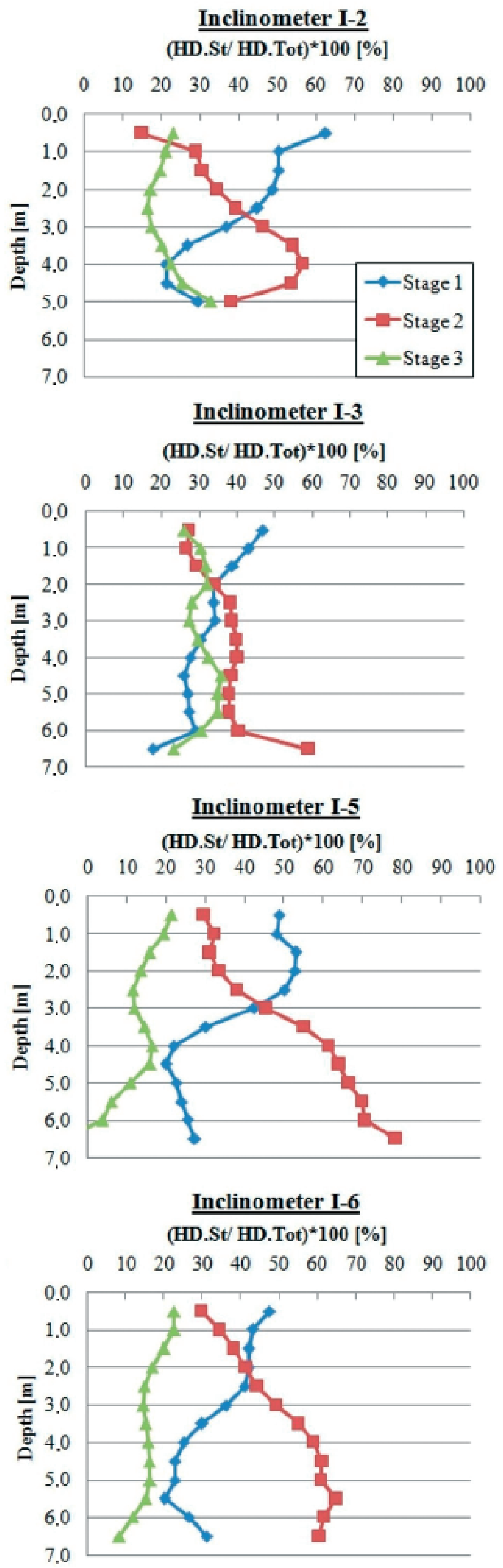

Figure 13.
Percentage share of horizontal displacements at each stage in total displacements

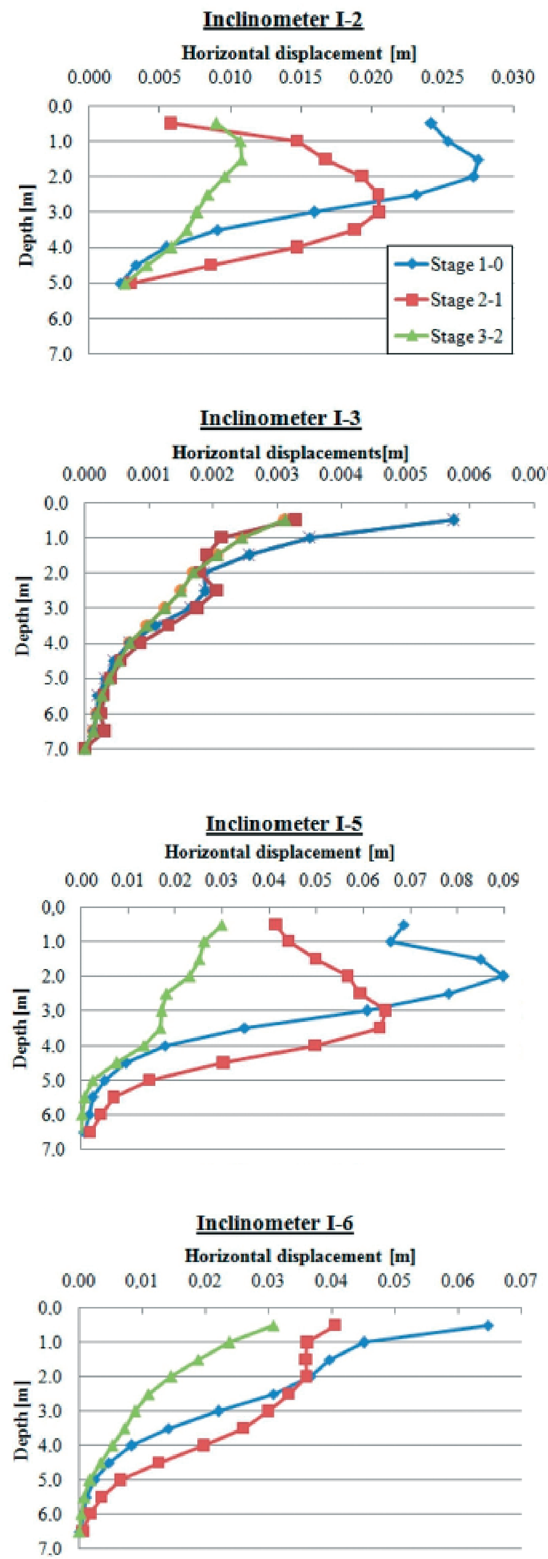

Figure 14.
Horizontal displacement on each stage of column formation

ing on the obtained data was excluded. The results can be explained by two phenomena. Firstly, during 30-day period pore pressure dissipated and soil rebound could have appeared provoking soil backwards movement into the direction of the column. Secondly, inclinometer casings made of plastic which are surrounded by ground-cement mixture show elastic properties. The casings, tight during the formation process, after some time caused soil backwards movement.

The results of inclinometer measurements were also presented in the form of percentage share of displacements registered after the particular stages (HD.St) in total displacements (HD.Tot.). It is clearly visible that after the first drop series (blue) most displacements occurred on the depth of 2 m. In turn, after the second series, maximal displacement values were observed on the depth of about 4 m below ground level. Displacements after the third series of drops are bigger on the depth of 4.5 – 5 m. However, their changes are not significant.

The deformation occurs typically on the depth of 2 and 4 m below ground level. These values correspond directly with the depth presumably reached by the column bottom after the first and the second formation stage. This observation may lead to the conclusion that the maximal displacement near stone column appear on the level of the column bottom.

After the first formation stage, the deformation observed in the highest measuring point (near ground surface) was about 50% of the total displacement, which corresponds with the results of ground uplift measurements. After the first series of drops, the uplift was about 50% of the total uplift (Fig. 10).

I-3 inclinometer showed similar displacement values at every stage of column formation. Figure 13 shows the results from every stage, which all indicate values equal to about 33% of total displacement.

The conclusions drawn from Figure 13 are completed by the value of horizontal displacements at every stage of column formation, which is shown in Figure 14. "Stage 2-1" marking means that the displacement value after the first formation stage was subtracted from the displacement value obtained after the second stage of column formation. Horizontal displacement values are given in meters.

On the basis of the presented results it can be concluded that the above phenomena are particularly visible for inclinometers placed in the nearest proximity of the column (I-2 and I-5).

After the first stage of column formation, these inclinometers indicated the biggest displacements at the depth of 2 m below ground level. In case of the farthest inclinometers, the maximal value was observed in the lowest measuring point. Similar displacements of I-3 inclinometer at every formation stage may be the result of its distant location from the column. The displacement values are very small (max 6 mm).

8. OBSERVATIONS AND CONCLUSIONS

The performed measurements allowed to determine the extent of the influence of stone column formation on the deformation of the surrounding soil (in the described soil conditions). On the basis of horizontal and vertical soil displacements, it was determined that the process influences the soil in the radius of 6 m from the column, which is equal to six times the diameter of the used rammer.

After the first stage of column formation, horizontal and vertical displacements measured in points located close to the soil surface constituted about 50% of total horizontal and vertical displacements respectively. Maximal values appeared at depths up to 2 m below ground level, depending on the distance between the inclinometer and the stone column. On this stage, the bottom of the column is probably located slightly deeper.

The second formation stage was marked by maximal deformations at the depth of 4 m below ground level. As it was determined during excavation, that was the approximate depth of the column bottom.

Soil deformations that appeared at the third stage of column formation were definitely the smallest and constituted about 20% of total displacements.

Considering the terminal displacements of the inclinometers located at the closest distance from the column, it can be supposed that the deformations of the adjacent soil correspond with the shape of the stone column. The biggest deformations indicated by the inclinometer located farther than at 3.5 m were observed close to the soil surface.

Significant asymmetry of displacements is characteristic to the entire structure. It is up to 300% for horizontal displacements, whereas for ground uplift – 200%.

The readings performed after 30 days from the moment when stone column formation was completed indicated that the inclinometers were displaced in the direction of the column.

What is noteworthy is the fact that the volume of backfill introduced into the ground (20.9 m^3) exceeds the stone column volume (16.1 m^3) by about 30%. Considering that the backfill density changes during ramming from $\rho_{d\,min}$ into $\rho_{d\,max}$, the initial volume is reduced to about 18.3 m^3, what still exceeds the volume of the column. Moreover, it should be noticed that the volume of uplifted soil was 7.6 m^3, what constitutes almost 50% of the column volume.

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