

Soil Overconsolidation Changes Caused by Dynamic Replacement

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Abstract. In the dynamic replacement method (DR) the soil is improved by initially dropping a large weight (typically 8-20 t) poulder from a significant height up to 25 m. The created crater is filled with a stronger material (gravel, rubble, stone aggregate, debris), and the poulder is dropped once or multiple times again. The construction of dynamic replacement pillars influences the parameters of the adjacent soil. It results from the energy generated by dropping a poulder into the soil. In the current practice, these changes are not taken into the account during the design. This paper focuses on the changes of overconsolidation ratio (OCR) and in situ coefficient of lateral earth pressure (K) values estimated base on cone penetration test (CPTU) and Dilatometric test (DMT) performed at a test site. A single column was constructed and the ground around the column was examined using CPTU and DMT, performed at different distances from the column centre (2, 3, 4 and 6 m) and at different time intervals (during construction and 1, 8, 30 days later). The column was constructed in so-called transition soils (between cohesive and non-cohesive). While interpreting the results of the research, the authors addressed the matter of choosing the procedure of OCR and K indication for transition soils (in this case described as silts and/or sandy silts). Overconsolidation changes may differ depending on the chosen analysis procedure (for cohesive or non-cohesive soils). On the basis of the analysis presented in the paper and the observation of soil (acknowledged as cohesive according to macroscopic observations) during column excavation, it was decided that for more detailed analyses methods dedicated to cohesive soils should be applied. Generally, it can be stated that although the changes were complex, DR pillar formation process resulted in the increase of these parameters. The average increases of OCR and K values were 25% and 10% respectively. The post installation values are not significant from the engineering point of view, but they represent the influence of the formation process of only a single column. The described results indicate that Priebe's column dimensioning method should be applied with caution, as it assumes the value $K=1$ which was not obtained in the described research. The results from the conducted tests indicate that different mechanisms occur during stone column formation with vibro-replacement and dynamic replacement. As the authors did not manage to find literature describing the results of K tests in the surrounding of a DR column, the presented results should be acknowledged as significant for designers who will apply the dynamic replacement method.

1. Introduction

In recent years, one of the most common technique of weak soil strengthening has been the dynamic replacement method. The method results in the construction of a grid of stiff, load bearing columns



formed in soil, which are usually made of coarse stones. Although the load from the built structure is placed mostly on the column, the adjacent soil is also affected. In the design process, the influence of column formation on the strengthening of the adjacent soil is not taken into account due to lack of the appropriate research in this field. This encouraged the authors to attempt to determine how the formation of a single rammed stone column influences the surrounding soil. Further research is planned to analyse a group of column.

2. Dynamic replacement technique

In the dynamic replacement method (DR) the soil is improved by initially dropping a large weight (typically 8-20 t) pounder from a significant height up to 25 m. The created crater is filled with a stronger material (gravel, rubble, stone aggregate, debris), and the pounder is dropped once or multiple times again. Further on, the created crater is again filled with the stronger material and the procedure continues, usually to the point when the penetration of the pounder becomes marginal. The procedure results in a column of a stronger material, which can sustain much higher loads than the soil in its initial condition. The most common DR column (pillar) diameter is about 2.5 m and their length is up to 5 m.

3. Current state of knowledge

The literature describing the influence of rammed stone column (DR) formation process on the surrounding soil is modest. There are only a few studies presenting the research on the abovementioned topic [1]. This paper takes into account the research on the influence on overconsolidation carried out by Wong and Lacazedieu [2]. They present an example of the use of stone columns in weak soil of thickness up to 9 m. Columns which were 2.5 m in diameter were spaced at 5.5 m from each other. They were formed from a 1.7 m thick work platform. As the columns did not manage to strengthen the soil at each depth, some additional overload and prefabricated drains were applied. Depending on the measuring point, the consolidation settlements varied from 0.8 to 1.0 m. It should be noted that the predicted settlement was 0.8 m. The authors indicate that stone column formation method diminishes the risk of secondary consolidation and the effect of soil overconsolidation. OCR values obtained during stone column formation (2.1 – 3.4) are much higher than the values determined on the basis of tests performed before the formation process (OCR=1.0). According to the authors, this is the result of the dynamic process of column formation and the application of huge energy. OCR values were calculated on the basis of the resistance measured by “field vane test” on the side of a column.

Considering the modest body of literature describing overconsolidation effects, the paragraphs below present a brief overview of this phenomena occurring in similar methods, i. e. vibro-replacement and dynamic consolidation. The literature analysing K changes in soil surrounding a vibro-replacement column is much richer than this presenting OCR changes. The research and numerical analyses indicate various estimations of K values, which is influenced e. g. by the special distribution of the columns. Elshazly et al. [3] report K value to be between 1.1 and 2.5, Elshazly et al. [4] between 0.7 and 2.0 and Watts et al. [5] between the initial value K_0 and passive pressure K_p . The drop in OCR values resulting from the application of vibro replacement method in overconsolidated soils is reported by Castro et al. [6]. The authors explain this phenomenon by the destruction of soil structure. In case of dynamic compaction, Kurek [7] presents the results of research on sands. The analysed sands were initially classified as normally consolidated on Robertson chart and after soil strengthening using dynamic consolidation – as overconsolidated. OCR values increased from ranging from 1-5 to 5-10

4. Field tests

The research was conducted on a 14 x 14 m test field situated in the north eastern part of Poland. CPTU, DMT soundings and mechanical drillings were performed in order to examine the soil conditions in the test field. According to the conducted analyses [8], the subsoil is made of four layers of soil:

- Layer I, down to 1.5 m below ground level (bgl), is composed from silty sands and sandy silts;
- Layer II, located between 1.5 to 2.5 m bgl, is made of silts;
- Layer III, situated down to 4.8 m bgl, consists of sandy silts and silty sand;

- Layer IV, fine sands constitute the bearing layer. The top part of the layer, located at 5.3 m bgl according to the mechanical drillings, which is lower than what was determined by the CPTU tests (4.8 m bgl).

The drillings resulted in the determination of the level on which groundwater occurred. The water table was situated at 3.0 m bgl and when drilling, it was met at 4.8-5.3 m bgl. The influence of DR column on the overconsolidation of the adjacent soil was analysed for the second (II) and the third (III) soil layer. The results of tests conducted in the first (I) layer may be incorrect due to the movements of the equipment used and to variable weather conditions. The fourth layer (IV) is the bearing layer.

The DR column was formed using the equipment that allowed a free drop of a 10 t barrel-like pounder from the height of 15 m. The rammer was 1.65 m high and its diameter was 1.0 m in the middle part and 0.8 m at the bottom. The mixture of fine gravel with coarse sand and rubble (in 1:1 proportion, 0-200 mm fraction) was used as backfill material. The column was formed by dropping the rammer onto the soil 36 times from different heights. The column formation was divided into three stages. The first 10 drops constituted the first stage, in which the formed crater was refilled after each one or two drops of the rammer. In the second stage (drops 11-24), the crater was refilled after each 3-4 drops. In the last stage (drops 24-36), the drop height was successively decreased. The division of the process into three stages was an important element of the applied methodology. The column's shape was examined just after all the other planned tests had been performed. The diameter of the column head varied from 1.9 to 2.0 m. In order to facilitate the calculations, in further parts of this paper we assume that column diameter $D_c=2,0$ m. The maximal column diameter measured during the excavation was 2.8 m and column length was determined to be $L_c=3,8$ m. The maximal diameter was situated in the middle of the weakest silty layer (figure 1, 2).

5. Methodology of the research on parameter changes of the column surrounding

The research aimed at determining the influence of stone column formation process on the basic parameters of column surrounding. In order to do it, CPTU and DMT tests were conducted in points located at different distances from the column and at different time intervals. The first series of tests ("a") took place before the column formation process and consisted in four CPTU tests performed at 2, 3, 4 and 6 m from the column centre, and 3 tests carried out using Marchetti dilatometer (DMT) at 2, 3 and 6 m from the column axis. Further tests were performed at the same distances from the column, in points located on the circumference of circles passing through the previous measuring points, with the minimal spacing between the measuring points equal to 0.5 m. The tests were conducted after the completion of: 1/3 ("b" series), 2/3 ("c") and the entire column ("d"), and then 1 ("e"), 8 ("f"), 30 ("g"), 34 ("h") days post construction. The tests were performed down to 6 m bgl. Static probe Hyson 200 kN produced by a Dutch company A.P van den Berg Machinefabriek was used in order to perform all the CPTUs and DMTs.

6. CPTU and DMT parameters

The first conclusions regarding the efficiency of soil strengthening and its influence on the adjacent soil were drawn while analysing the changes of cone resistance q_c in time. It was because this parameter characterizes the general bearing capacity of the soil. Figure 1 shows the results of penetration tests performed 30 days after column construction ("g" series) in relation to the average value of resistance from "a" series, compared to the column's shape.

The sequence of changes is similar for all the performer tests. However, it is remarkable that the increase of q_c was noted only in the second layer in almost every measuring point, whereas in other layers the graphs often intersect. Moreover, just above the ceiling of the bearing (deepest) layer a drop of the q_c value was noted, together with a large changeability of the results from the surface layer. The general analysis of dilatometric pressures P_0 and P_1 was based on Figure 2, in which the parameters of probing performed 30 days post construction were compared to pressure values P_0 and P_1 obtained before the construction of the column. Apart from the first layer, in almost all measuring points, probing

parameters increased with time. The increase seems to be the most considerable at the bottom part of the column and the least important in the second (silty) layer.

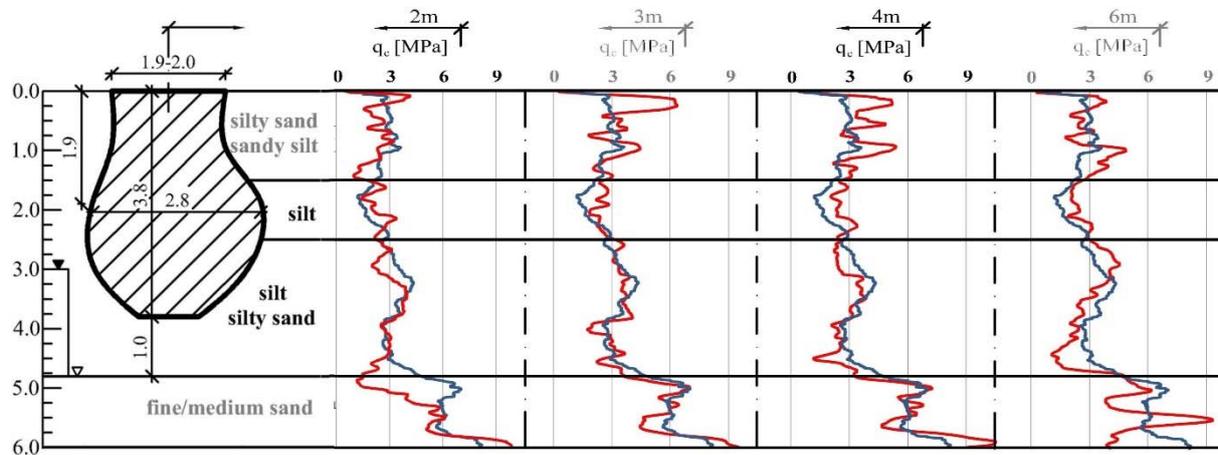


Figure 1. Cone resistance q_c values obtained in „a” series (blue) and „g” (red) series

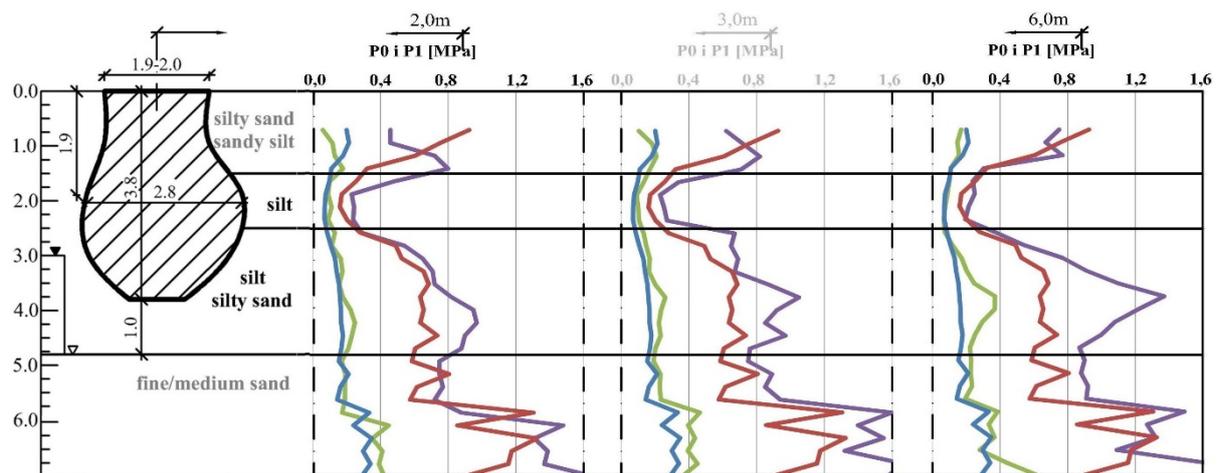


Figure 2. DMT test parameters (P_0 and P_1) before column formation (blue and red) and 30 days' post construction (green and violet)

Although very general, the presented analysis shows that different types of tests gave different results when it comes to the level of soil strengthening. These results are typical of tests carried out after the dynamic strengthening of soil. The results of dilatometric test are more sensitive to changes of horizontal stress than CPT. It can be proved by the comparison of dilatometric module with cone resistance for tests performed before and after the compaction. This kind of comparison is presented in [7].

6.1. Choosing the way of interpretation of the overconsolidation parameters

The manner of how overconsolidation parameters are assessed depends on the examined soil type. This is due to the fact that different procedures are applied for the interpretation of DMT and CPTU tests for cohesive and non-cohesive soils. For cohesive soils, it is the most common to use OCR value and in case of overconsolidation in sands, M_{DMT}/q_c relationship is usually taken into account. Figure 3 shows diagrams presenting the classification of the examined soils (CPTU and DMT on Figure 3a and Figure 3b respectively). The diagrams indicate that the soils consisted of silty sands and sandy silts. They are so-called transition soils between cohesive and non-cohesive soils. It should be added that during

mechanical drilling and macroscopic diagnosis the soils were identified as sandy silts close to silty sands. Robertson's diagram [9] (Figure 3a) indicates that the soils are classified as normally consolidated.

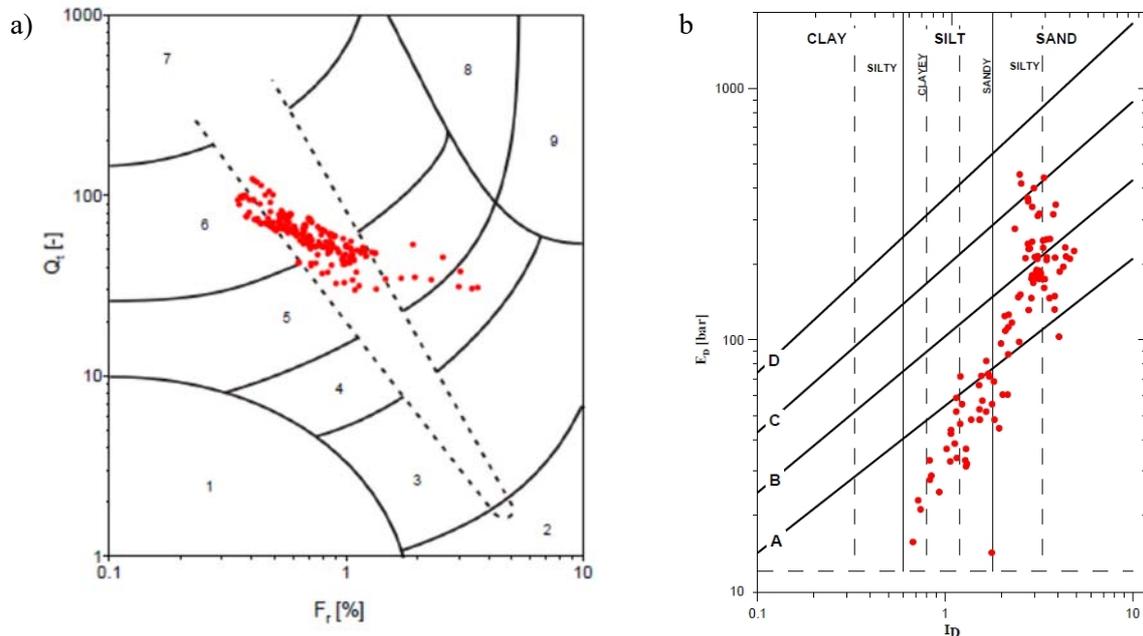


Figure 3. Classification of the examined soil on the diagrams of a) Robertson, b) Marchetti

While trying to estimate the overconsolidation index using Wierzbicki's method [10], OCR values oscillate between 1 and 2, no matter if they are treated as cohesive or non-cohesive. The overconsolidation of the examined soil on particular stages of the test can be first of all estimated on the basis of the analysis of K_D changes (for cohesive soils) and of M_{DMT}/q_c relation (for non-cohesive soils). These two approaches were applied to compare the results for points located 2 m from the column axis (Figure 4).

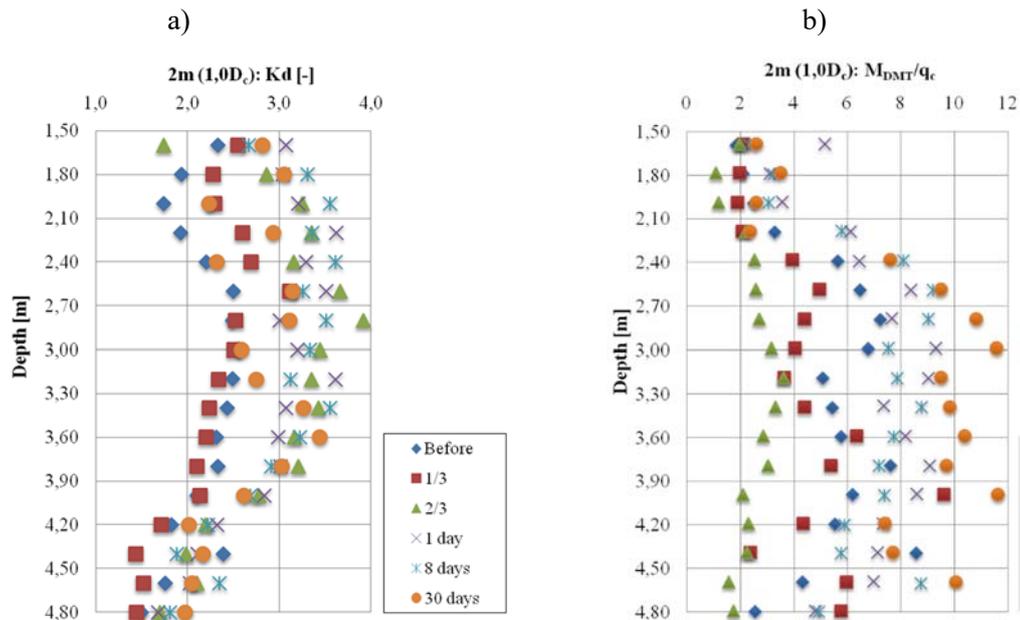


Figure 4. Overconsolidation changes estimated on the basis of:
a) K_D changes, b) M_{DMT}/q_c relationship.

In estimations the authors have applied a kind of simplification useful also in further analyses. It aimed at a clearer presentation of the research outcome and consisted in averaging the results of “c” and “d” series (described as “one day post-construction”) and in averaging the results obtained from the point located 6 m from the column in “g” and “h” series (described as 30 days post-construction). The results from points located at 2 and 3 m from the column from both “g” and “h” series were not averaged because of the excavation carried out between the two series, which might have influenced the results from “h” series. According to the numerical analysis, only points at 6 m from the column were out of reach of soil wedge resulting from the excavation of the column [11].

Depending on the applied approach, the obtained values may indicate two situations: soils were recognized as normally consolidated (KD) at each stage of the research or were treated as overconsolidated (M_{DMT}/q_c) 30 days’ post construction. The increase of ratio M_{DMT}/q_c above 10 which occurred at the last stage of the research is the factor that allows the soil to be classified as overconsolidated. Figure 4b shows that at the depth of 1.5-2.2 m bgl, the ratio M_{DMT}/q_c is still exceptionally low, which proves the presence of silty soils. Below that depth, the ratio 5-10 is typical of normally consolidated sands and the ratio above 10 – for overconsolidated sands [12].

Overconsolidation changes may differ depending on the chosen analysis procedure. When applying K_D to the second stage of column formation, a remarkable increase of this parameter can be observed one day post construction. The analysis of M_{DMT}/q_c ratio indicates an important drop of parameters values during column formation (1/3 and 2/3) and then an increase one day after column construction. It probably results from low q_c values. That in turn may indicate that static probing is more sensitive than DMT to the destruction of soil structure caused by large displacements of soil noted up to 6 m from the column. Although dilatometric test is a focused research it may not enable to detect this fact because of large total stress in the examined area.

On the basis of the presented analysis and the observation of soil (acknowledged as cohesive according to macroscopic observations) during column excavation, it was decided that for more detailed analyses methods dedicated to cohesive soils should be applied. Two parameters related to the soil overconsolidation effect were estimated: overconsolidation ratio OCR and the coefficient of lateral earth pressure K. In pre-construction phase many procedures were verified and then a procedure was selected for each parameter. Finally, the overconsolidation ratio OCR was calculated on the basis of DMTs, using the formula presented by Simonini et al. [13]:

$$OCR=0,66(K_D)^{1,05} \quad (1)$$

When considering young silty soils, the formula shows the agreement between DMTs and laboratory rests results [10]. The lateral earth pressure coefficient was estimated on the basis of CPTUs and DMTs using the formula presented by Baldi et al. [14]:

$$K=0,376+0,095K_D-a(q_c/\sigma'_{vo}) \quad (2)$$

where: $a=0.0046$ for soils in natural conditions, however in the above formula, a coefficient for native cohesive soils was corrected by 0.002 in young subsoils, according to [15] and [16].

6.2. Results of the research on the changes related to the soil overconsolidation effect (OCR and K)

For the purpose of analysis, the vertical axes in the figures below do not present the depth (H), but its ratio to the column length (H/L_c). The solid black line indicates the depth of the third layer’s ceiling. The dotted line indicates the depth of the column base. The analysis of overconsolidation ratio OCR changes for layers II and III is presented below in form of the graphic representation of the results shown in Figure 5 and Figure 6. The blue line marks the value of OCR coefficient before column construction. Depending on the depth, the initial overconsolidation ratio varies between 1.25 and 1.75. As a result of column formation OCR values increased in all the measuring points to the column bottom (Figure 5).

This increase is fully visible only a day post construction. During the construction process, OCR values increase gradually.

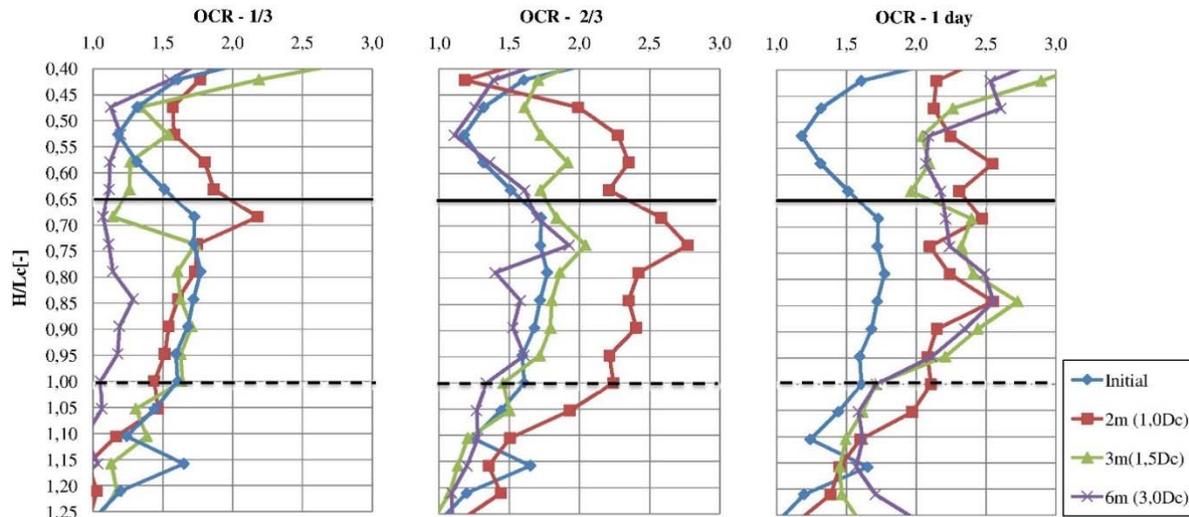


Figure 5. Values of overconsolidation ratio at different stages of installation process

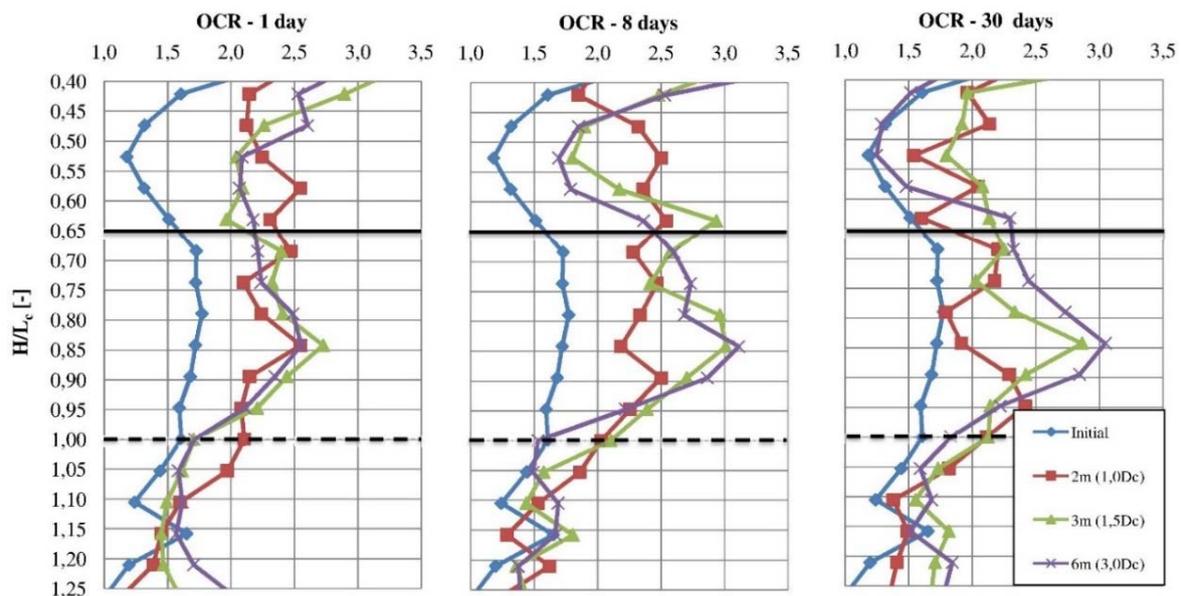


Figure 6. Values of overconsolidation ratio at different post treatment time intervals

The changes of OCR values appearing after column formation occur also only to the depth of column base. OCR values 1 and 8 days post construction are similar, but they decrease 30 days after column construction (Figure 6), except for the peak at the depth $H/L_c=0.85$ at 6 m from the column. According to the authors, this is the result of the dissipation of the excess of water pressure in soil pores, a so-called soil rebound. It is remarkable that the OCR values for layer III noted 30 days post construction in a point located 2 m from the column are closer to the initial value than those measured at 3 and 6 m from the column. This fact confirms the thesis presented above. The dissipation of the excessive water pressure in pores was the most rapid close to the column, where privileged filtration ways occur.

These results suggest that the stresses induced in soil decreased within time (dissipation) and thus the OCR values partly diminished in comparison to the maximal ones. In general, it can be noticed that the average value of OCR increased by about 25% of the initial value (from average 1.54 to average 1.93). It is important to remember that the research was conducted on a single column. If a group of columns had been constructed, OCR values would probably have increased because of the neighbour columns (columns are spaced at less than 6 m usually). The final values of OCR coefficient were close to those minimal obtained by Wong and Lacazedieu [2]. Dynamic compaction of sands induces higher increase of OCR values than described in this research. However, a more important conclusion is that OCR parameter drops within time as a result of soil rebound and does not increase because of soil aging. The analysis of lateral earth pressure coefficient K was performed in a slightly different way than the OCR analysis. The latter indicated that K changes depending on the distance from the column during construction (Figure 7) and after the completion of this process (Figure 8).

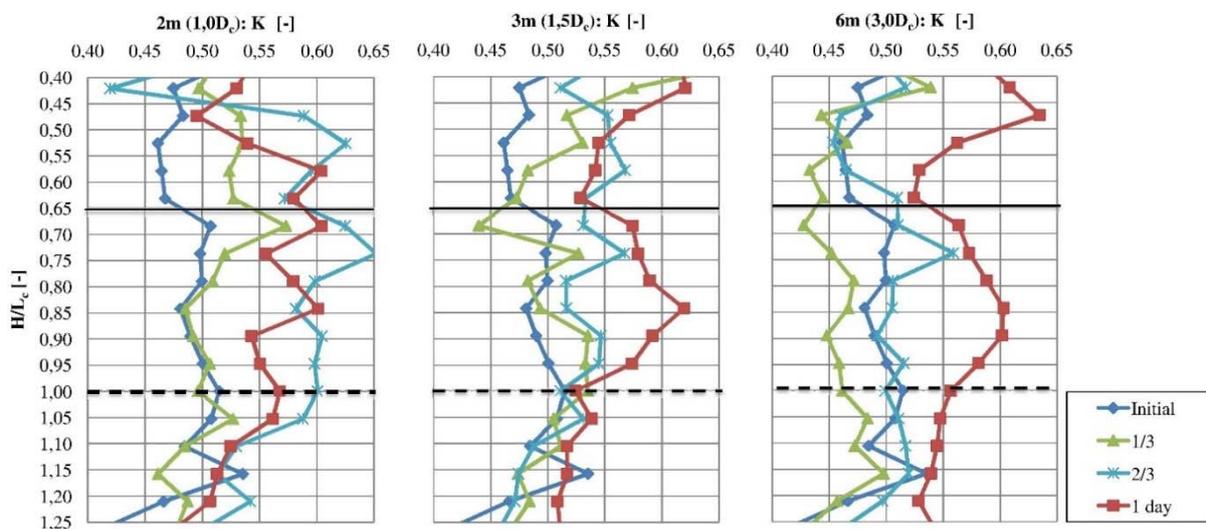


Figure 7. Values of K measured at different distances from the column during ramming

The initial value of K was about 0.50. When analysing the values of K obtained in the same time but at different distances from the column (Figure 7 and 8), it can be noticed that the increase of this parameter was a complex process, which depended on both time and the distance from the column centre. When 1/3 of the column was completed, K changes were noted only in layer II at the distance of 2 m from the column. After the construction of 2/3 of the column, the value of K increased in the measuring point located at 2 m from the column axis, at the depth up to $1,0L_c$. At a more distant point, located at 3 m from the column axis, the increase was visible only in layer II, and in the most distant point it was not observed. One-day post construction, regardless of the measuring point location, the value of the discussed parameter was about 0,55-0,60 on the entire length of the column (20% increase). During the first 8 days post construction, no K changes were observed in the measuring point at 2 m from the column. Soil performance at the distance of 3 and 6 m was different in layer II (decrease of the analysed value) and different in layer III (a slight increase of K). After a month post construction, K values measured at 2 and 3 m from the column axis stabilized and reached about 0.55 in layer III and 0.50 in layer II. In the most distant point they varied the most (in layer II they dropped beneath the initial values and at the depth $0,85L_c$, they remained as big as 8 days post construction). This means that between the 8th and 30th days post construction in the second layer and in the upper part of the third layer there was a slight drop of K , whereas in the lower part of layer III the examined values did not change. It was also noticed that the increase of K values in all points was recorded only at the depth of the columns base. In general, it can be concluded that the changes of K values during and after the column formation were not large. The average value of K 30 days' post construction was about 0.50 in

second layer and 0.55 in third layer. It means that the value increased only in layer III by 10 % in relation to the initial value (0.5).

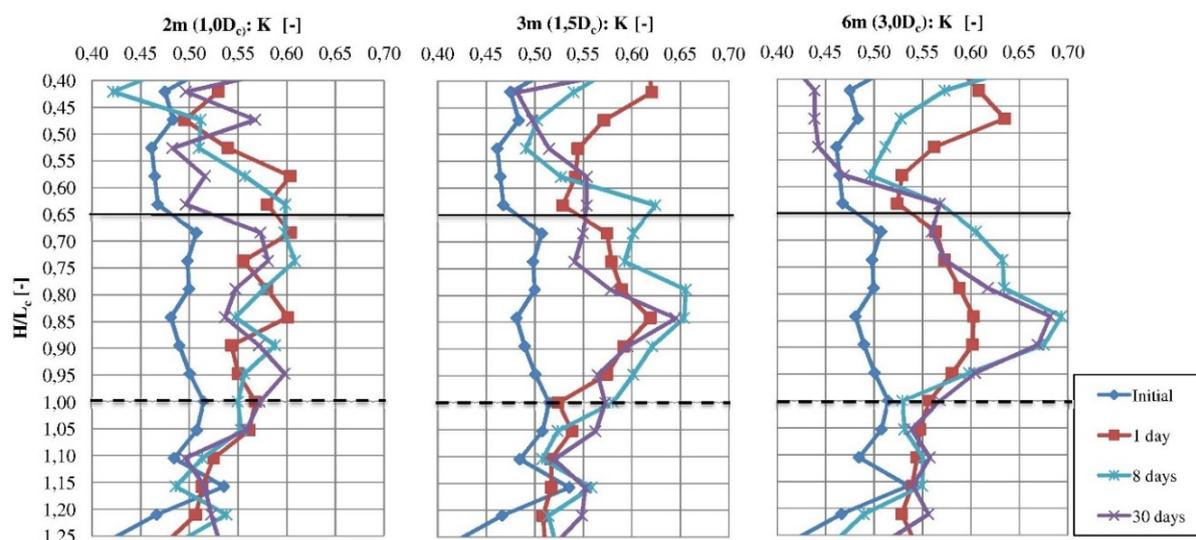


Figure 8. Values of K measured at different distances from the column after installation

While analysing K changes in time and at different distances from the column, it can be noticed that they are similar to the dependences presented in OCR analysis. This results from the fact that both parameters are related to each other and that they were determined, among others, on the basis of the same parameter of penetration test DMT, i. e. a non-dimensional index of horizontal stress KD. Comparing the obtained results with K increase described in the literature about vibro-replacement columns (point 3), it should be noted that the use of vibrator results in much higher increase of this parameter. Similar observations were presented in [7], in which he compared dynamic replacement with vibro-replacement carried out in sands.

As there is no literature describing the results of K tests in the surrounding of a DR stone column, the presented results should be acknowledged as significant for designers who will apply the dynamic replacement method. The authors highlight that in the primary Priebe's method [17], the settlements are calculated for weak soil with $K=1$. According to Priebe, this is a simple way of reflecting the influence of the column on the surrounding soil. As in case of a vibro-replacement column this is a safe approach, in case of a dynamic replacement column it may lead to significantly lower settlement estimations while designing the column. In order to confirm the abovementioned recommendation, the authors are planning to perform similar tests on a group of DR columns.

7. Conclusion

In the conducted research, the influence of a single DR pillar formation process on the overconsolidation of the adjacent soil was observed. The influence was represented by the change of two parameters: overconsolidation ratio OCR and coefficient of at lateral earth pressure K, analysed in function of time and distance from the column. Although the changes were complex, DR pillar formation process resulted in the increase of these parameters. The average increases of OCR and K values were 25% and 10% respectively. The post installation values are not significant from the engineering point of view, but they represent the influence of the formation process of only a single column. The described results indicate that Priebe's column dimensioning method should be applied with caution, as it assumes the value $K=1$ which was not obtained in the described research.

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