TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
ENVIRONMENT ENGINEERING | ŚRODOWISKO
1-Ś/2013

PIOTR KANTY*

RESEARCH ON THE INFLUENCE OF THE APPLIED STONE COLUMN FORMATION METHOD ON THE CONSOLIDATION TIME OF THE SURROUNDING SOIL

BADANIA WPŁYWU TECHNOLOGII FORMOWANIA KOLUMNY KAMIENNEJ NA CZAS KONSOLIDACJI JEJ OTOCZENIA

A b s t r a c t

Dynamic replacement (DR) and vibro replacement (VR) are the most common methods of stone column formation applied in Poland. A stone column acting as a drain is considered as a method of speeding up the soil consolidation process. However, the influence of the column formation process itself on the consolidation time is unknown. Dynamic effects as well as the destruction of soil structure taking place during DR column formation may extend the time of soil consolidation in comparison to less invasive methods, like vibro replacement. To verify this thesis, laboratory model tests of three VR columns and three DR columns were conducted at the geometric scale 1:40. Weak soil was imitated with very soft clay and the column material – with gravel. In order to identify phenomena occurring during the investigation, the clay itself was tested as well and FEM was applied. The initial parameters used in the numerical analyses were taken from standard laboratory tests.

Keywords: dynamic replacement method, rammed stone columns, psychical modelling

S t r e s z c z e n i e

W Polsce kolumny kamienne kształtuje się najczęściej metodą wymiany dynamicznej lub wibrowymiany. Uznaje się, że kolumna kamienna pracująca jako dren przyspiesza proces konsolidacji podłoża. Nie wiadomo jednak, jak proces sam formowania kolumny wpływa na czas konsolidacji. Możliwe, iż efekty dynamiczne ,jak i zniszczenie struktury gruntu, towarzyszące wbijaniu kolumn w metodzie wymiany dynamicznej, wydłużają czas konsolidacji podłoża w odniesieniu do technik mniej inwazyjnych, jak na przykład wibrowymiana. W celu weryfikacji tej tezy wykonano laboratoryjne badania modelowe trzech kolumn wibrowymiany i trzech kolumn wbijanych. Badania wykonano w skali geometrycznej 1:40. Za grunt słaby posłużyła miękkoplastyczna glina, za materiał kolumn żwir. W celu lepszej identyfikacji zjawisk zachodzących podczas badań wykonano również badanie samej gliny bez kolumny oraz posłużono się metodą elementów skończonych. Parametry wyjściowe do analiz numerycznych uzyskano ze standardowych badań laboratoryjnych.

Słowa kluczowe: wymiana dynamiczna, wbijane kolumny kamienne, badania modelowe

* M.Sc. Kanty Piotr, Department of Geotechnics and Roads, Faculty of Civil Engineering, Silesian University of Technology.

Symbols

DR – dynamic replacement
VR – vibro replacement
ϕ' – effective angle of internal friction [°]
c' – effective cohesion [kPa]
k_{10} – hydraulic conductivity at 10°C [cm/s]
Mo – oedometric moduluj [MPa]
σ – stress [kPa]
w_{ini} – moisture [%]
ρ_d – relative density [g/cm^3]
c_u – shear strength [kPa]

1. Introduction

1.1. Description of the method

Both Dynamic Replacement (DR) and Vibro Replacement (VR) techniques are used to reinforce weak soils (especially soils which can be significantly compressed, e.g. soils with organic content, weak clay soils and loose anthropogenic soils).

Introducing stone material into the soil requires the use of equipment that enables free drop of an 8–20 t rammer from a height up to 25 m [12]. This kind of equipment with a suspended rammer used for stone column formation is presented in Fig. 1a. First of all, the dropping rammer forms a crater which is filled with coarse-grained material (such as rubble, stone aggregate, blast furnace slag, burnt shale and debris). The material is rammed until it is introduced into the surrounding soil. When the crater becomes empty again, it is refilled with the material and the sequence is repeated. The formation process continues until the soil becomes significantly resistant to further ramming. The procedure ends when an aggregate column is completed. The vertical bearing capacity of the column is higher than the vertical bearing capacity of the soil naturally occurring on site. In Poland, the most common column diameter is about 2.5 m and its length is up to 5 m [9]. The particle size of the aggregate used for stone column formation is generally 30/120, 30/300, 0/500 mm [8].

In the vibro replacement method, columns are formed with a special vibrator. The formation process can be divided into three main stages:
– The vibrator penetrates the soil to the design depth. The penetration process is often aided by compressed air or water jetting, or by the use of air-water mixture.
– The crater is filled with aggregate. The vibrator is lifted and at the same time, a portion of aggregate is introduced from above to the main part of the vibroflot and then released through a hole located in the main part of the vibroflot. The aggregate of previously determined particle size, is introduced to the main part of the vibroflot through a special feeder in the upper part of the equipment (Fig. 1b).
– The introduced aggregate is compacted as the vibrator is lifted in a reciprocating motion. Downward movements of the vibrator displace and densify the aggregate. The compaction proceeds by stages, every 0.3–0.5 m.

a) b)

Fig. 1. Equipment for a) DR and b) VR column formation

During the VR column formation process, no soil is withdrawn to the surface and therefore there is no need to remove big quantities of soil. The columns formed with the use of vibro replacement method are also called gravel columns. Their diameters vary between 0.6 and 1.2 m and they are up to 45 m long. The column diameter depends on the vibrator dimensions. In general, the size of the used aggregate is 0–31.5 mm, which is determined by the vibrator shape. Particles of bigger size could constitute obstructions inside the vibrator.

Both DR and VR columns are designed in triangular, rectangular and hexagonal grids [6]. Their axial spacing differ due to different stone column diameters. What can be similar in both techniques are the values of the soil replacement ratio, that is the ratio of column section surface to the surface of its immediate vicinity (the so called unit cell [6, 11]).

1.2. Description of the research problem

In the case of both methods, cone resistance changes occur in the soil adjacent to the stone column, this is reflected in changes of strength and shear parameters. This type of change is the object of the author's research [15]. For information on the aforementioned changes in the VR method, see [1]. These changes are due to the specificity of a given technology and to the drainage function of the columns. The drainage effect of VR columns is described in international literature [2–4], whereas the case of DR columns has yet to be examined. The research described in [13, 14] is one of the few attempts to examine this question.

While analytical methods of designing vibro-column reinforcement exist [6, 10], there are no algorithms for driven columns which would take into account the specific method of their construction [6–8]. While designing such columns, two factors are taken into consideration: the column's bearing capacity; settlements of the system consisting of the column and its surrounding [9]. The drainage effect is very rarely taken into account in projects, whereas it is visible during the construction of reinforcements realized with the use of DR and VR methods. As an example, we propose the photo (Fig. 2) of the area reinforced with the DR method. This photo was taken on one of the building sites in Poland.

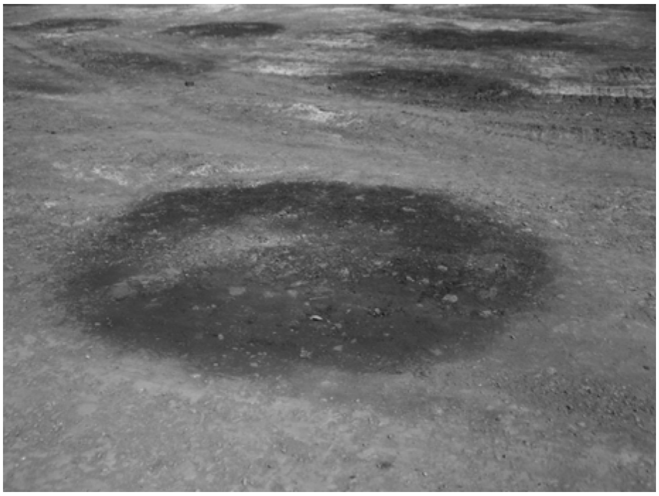


Fig. 2. Area reinforced with the DR method, visible damp spots in places where columns are located

The research described below is the first attempt of the author to determine, via laboratory tests, the efficiency of the DR column drainage in comparison to the VR column.

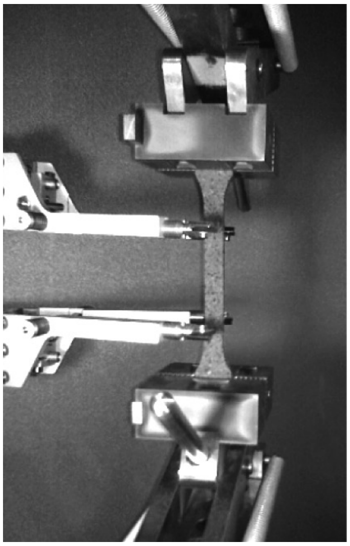
2. Research methodology

2.1. Description of the test stand

The research aim was to construct three DR and three VR columns and to perform one model test without columns.

All the tests were performed at a geometric scale of 1:40, inside a tube which was 30 cm in both diameter and height. In every test, the tube was filled with sand up to 12.5 cm, on which a 12.5 cm layer of clay was placed (Fig. 3). Sand represented the strong soil layer and clay represented the layer of weak soil that needed to be reinforced. Sand and clay were placed layer by layer (about 2.5 cm each) and always compacted in the same way. The tube was placed on non-woven geotextile fabric, which allowed water to drain freely. The next step consisted of placing the load on the model without column and, for the DR and VR models, in column formation.

a)



b)

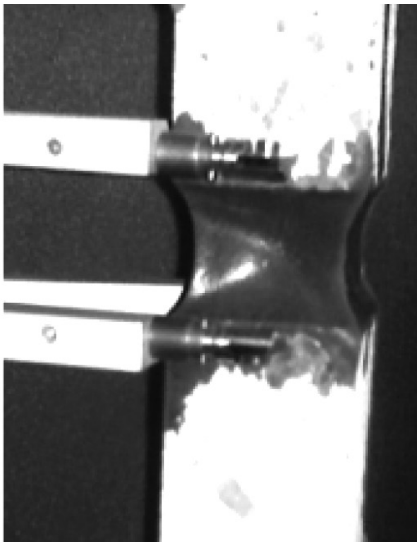


Fig. 3. Schematic research models: a) with column, b) without column

Soil parameters used in the research (Table 1) were determined on the basis of standard laboratory test.

Table 1

Materials parameters used in laboratory tests

Soil type	ϕ' **[°]**	*c'* **[kPa]**	*k* **[cm/s]**	*Mo* **[MPa] for** σ **= 2.5–5.0 kPa**	w_{ini} **[%]**	ρd **[g/cm³]**	c_u **[kPa]**
Silty Clay	9	27	$2.6 \cdot 10^{-6}$	0.27	46.6	1.20	13
Sand	41	0	0.01535	5.78	0.1	1.91	–
Gravel	44	0	0.09690	7.14	0.1	1.70 (VR) 1.84 (DR)	–

2.2. Column formation

DR columns were formed with a 200 g steel weight which was 5 cm in height and 2.5 cm in diameter. Every column was formed by 10 drops from a height of 70 cm and 3 drops from 35 cm. After each drop, the formed crater was refilled with gravel. When the rammer did not penetrate the soil anymore, the column construction was completed (Fig. 4a).

To form VR columns, a 5-cm-diameter tube was screwed in up to the required depth and then unscrewed, removing the clay to the surface of the ground. The formed crater was filled from above (Fig. 4b). In order to prevent dynamic effects, the column material was not compacted, as happens in real conditions when the vibrator is pulled out in a reciprocating motion.

a) b)

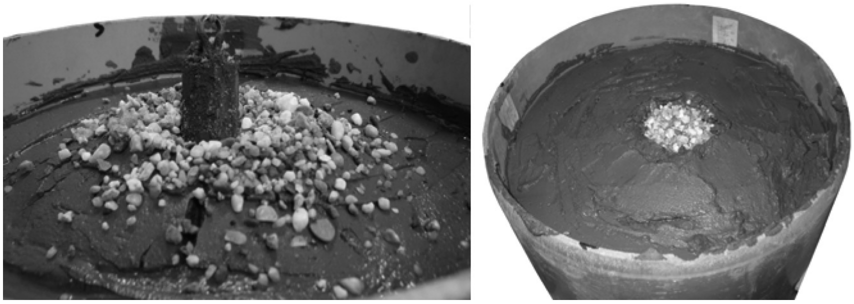


Fig. 4. a) the last stage of DR column formation, b) completed VR column

In spite of the different densities of the gravel that the columns were formed from, volumes of both columns were similar (1200 m^3 and 1140 m^3).

2.3. Settlements measurements

When the columns had been completed, loads with a total mass of about 39.3 kg were placed on each sample. Steel loads (Fig. 5) were put one by one on the surface of the samples. The operation lasted approximately 10 minutes. This induced stress of about 5.6 kPa. Sensors accurate to 0.001 mm were used to measure vertical displacements. While the loads were being placed, measurements were performed by three sensors located close to the edges (Fig. 5). Two hours later, only one sensor located in the center of the upper load was used. The measurements were conducted over a 1440 hours (60 days) period. The readings were performed initially every 10 seconds, later, every 2 minutes and in further stages, every 20 minutes.

Fig. 5. Samples during the consolidation process: a) within two hours of completion

2.4. Moisture changes tests

60 days later, after final vertical displacements had been registered, test systems were successively dismantled and samples were collected in order to conduct moisture tests. The mentioned samples were taken from 5 levels: 4 and 8 cm (sand), 14, 18 and 22 cm (silty clay) measured from the bottom of the tube, according to Fig. 6. At each level, 12 samples were collected: four at 4, four at 8 and four at 12 cm from the column axis. They were taken from an axes perpendicular axes of the tube. Moreover, 5 samples of material were collected from different levels on the axis of the system. In total, moisture of about 450 samples was examined. The moisture values of samples taken from the same localization were averaged.

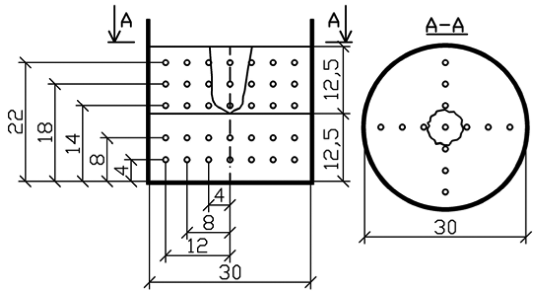


Fig. 6. Localization of the points where the samples for moisture tests were taken

Consolidation curves obtained from measurements of vertical displacements were processed on a spreadsheet. The results for DR and VR models were interpreted on the basis of the averaged values of the measurements.

3. Laboratory tests results

The key results of the conducted research are presented and discussed below. These are consolidation curves of column-surrounding weak soil system and soil moisture changes that vary depending on the distance to the column.

3.1. Consolidation curves of the test system

Figure 7 presents consolidation settlement values for models with DR and VR columns, as well as for the weak soil without column. The first minutes of the test, when the load was being placed on the samples and immediate settlements occurred, are not presented on the graph (Fig. 7a, b).

The differences between consolidation settlements values for DR and VR columns, shown in Fig. 7a, are minor (about 6%). Settlements of DR system are smaller, which is probably due to the difference in column material density, as DR column material is more compact. Smaller settlements may also be the results of the column formation method itself, which changes the parameters of the surrounding soil.

The settlements for the model without column were almost twice as big as those for the models with columns.

a)

b)

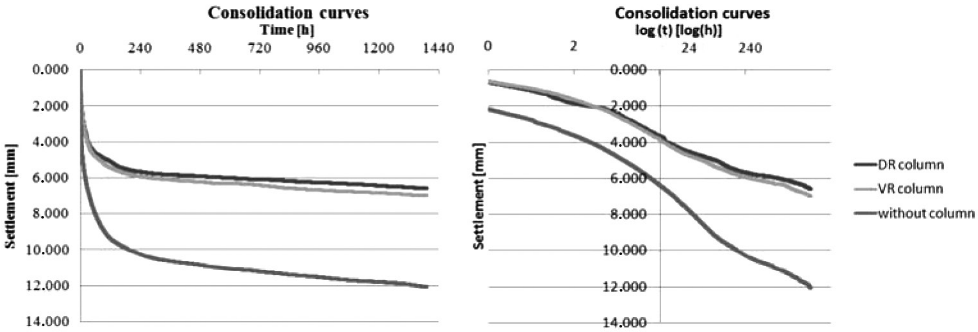


Fig. 7. Averaged consolidation curves for particular models

In this paper, we do not analyse the values of settlements, but their changes over time (the inclination of consolidation curves). It should be noted that the consolidation curves for both models with columns are perpendicular almost from the beginning of loading. It is clearly seen on the graph in logarithmic time scale (Fig. 7b). The behaviour of the model without column is similar up to a certain point after loading, when the consolidation curve becomes more inclined. It can be explained by slower filtration consolidation. Thus, it seems that the method of column formation has no significant influence on the time and course of consolidation process of the column surrounding. Both DR and VR columns accelerate the soil consolidation process in the same way.

3.2. Moisture

Samples for moisture investigation were collected as described above. Initially, the average value of clay moisture for the DR and VR column models, as well as for the model without a column, were 46.0% (±0.5%). The initial values of moisture for sand were equal (0.1%). After 60 days of consolidation, different moisture values for cohesive soil and underlying sand were registered, depending on their distance from the system axis. Fig. 8 presents the results of the investigation.

It was observed that the moisture of soil in the DR column model is higher in almost every measuring point than the moisture in the VR column system. The differences are insignificant (about 0.5%). Test precision was also determined to be 0.5%. Higher moisture values for DR columns system may be related to the lower filtration capacity of these type of columns. The inclination of moisture measurements results is noticeable in both cases. In the upper part of the system (h = 22 cm), moisture values are similar and are not influenced by the distance from the column (Δ = 0.5%). It is clearly visible in the lower part of silty clay (h = 14 cm) that the moisture value drops in the vicinity of the column and rises next to the tube sides (Δ = 2.0–3.0%). When it comes to sand, the differences are not significant

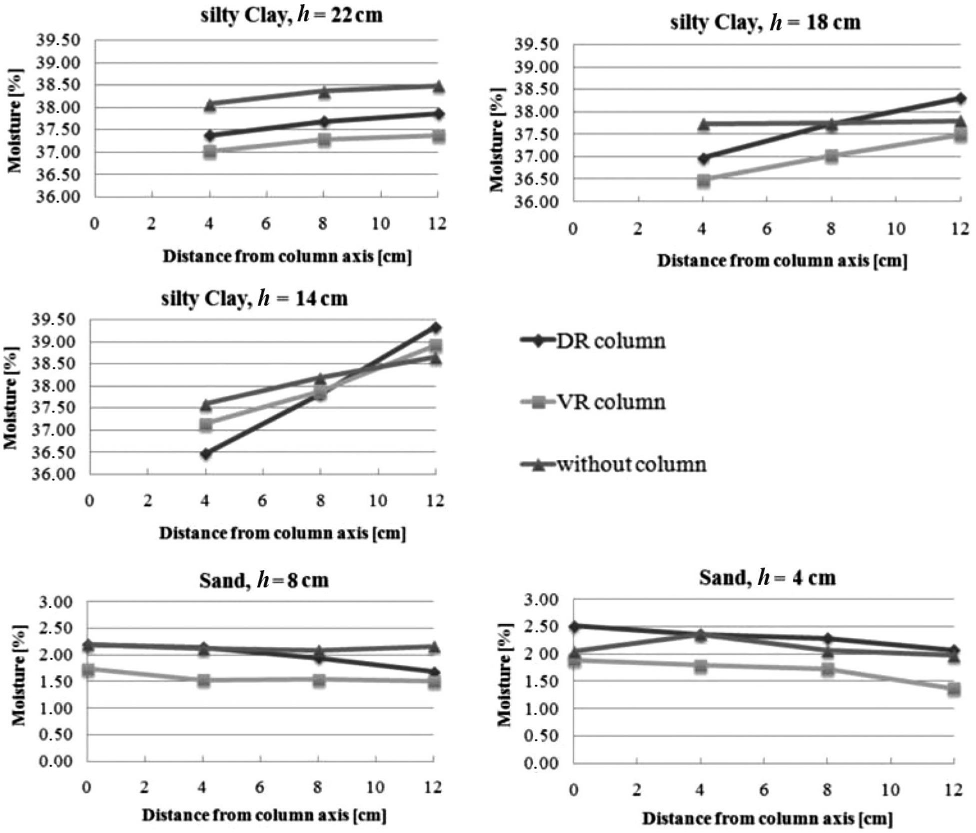


Fig. 8. Results of moisture investigation of the measurement system

(Δ = 0.5%), but moisture values tend to be higher in measuring points located under the column. The measurements indicated the highest moisture values under the column and the lowest in the sand adjacent to the tube sides. These observations indicate the existence of vertical and horizontal water flow in the analyzed system. The influence of vertical filtration is distinctive.

The interpretation of the results of measurements performed in the system without a column is more difficult. The upper part (h = 22 cm) of the system without a column showed higher moisture values then the models with columns and the results were the same for all the measuring points. It proves that the columns improve the filtration of the entire system and that the soil moisture in the upper part decreases more quickly. However, the differences are minor (Δ = 0.5–1.0%). The situation in lower parts of clay is similar only in the measuring points located in the closest vicinity the centre of the system. The closer the sides, the moisture values become the same or even (in the system without column) they are smaller than others (h = 14 cm). When it comes to sand, the moisture values of the system without a column are similar to the values of VR column. What should be noted is the inclination of the consolidation curves in the model without column – at every level, it is flatter than in the DR and VR systems, which proves a lack of horizontal filtration in that system.

4. Numerical model of the system without column

In order to understand better the phenomena which occurred during laboratory tests, a numerical model of the test system was elaborated in FEM software Z-Soil. The form of laboratory system was used to create a numerical axi-symmetrical model which aimed at reflecting the course of the test performed without a column. The Coulomb-Mohr material model was applied, with Menetray-William (M-W) modification and non-associated flow rule [17]. Initial stresses were generated assuming normal soil consolidation. The calculations took into account soil deformation resulting from the initial consolidation. First of all, typical values of strength and shear parameters of soil, determined on the basis of laboratory tests, were used in the calculations. Then, by trial and error, some chosen parameters of the model were modified in order to obtain the same numerical consolidation curve as the one from laboratory tests.

Hundreds of analyses with various material parameters proved not enough to obtain a numerical curve which would be the same as the curve obtained in laboratory tests. On the other hand, three phenomena were identified:

– Non-linear elasticity: while the load was being placed on the soil in the laboratory, the soil behaviour was characterised by non-linear elasticity. Using the hyperbolic elastic model of Duncan-Chang [5], attempts were made to obtain results convergent with the first few minutes of laboratory test. Satisfactorily true results were obtained up to the point in which the last load was placed.
– Yielding: after the last load had been placed, a momentary but clear increase of settlement was noted which was disproportionate to the value of the applied load. It has been observed that some clay was pushed out through the space between the tube sides and the load's base, a few millimetres smaller in diameter. The soil yield. It was impossible to reflect these results in the Duncan-Chang model. The results obtained from the Coulomb-Mohr model (M-W) were not satisfactory either. Further analyses omitted the loading stage and tried to find similarities in other parts of the consolidation curve.
– Creep (secondary consolidation): numerical analyses of system deformations that only took into account the primary consolidation showed that the process ends much before the end of the test. The last sections of the consolidation curve are flat, the same as Terzaghi's theoretical curve of uniaxial consolidation [16]. Only after secondary consolidation (creep) in the logarithmic function [17] has been taken into consideration in the analyses, the results were convergent nearly on the entire consolidation curve. In Z-Soil system, according to the formula:

$$\varepsilon^{cr} = \varepsilon^{e}_{\text{inst.}} f(t) = \sigma C(t) \qquad (1)$$

strain due to creep (ε^{cr}) is proportionate to temporary elastic deformations.

The function $C(t)$ described by the following formula was chosen for the model:

$$C(t, t_o) = A \cdot \ln(1 + Bt) \qquad (2)$$

where:

t_o, t – initial time of the analysis and the time in a particular computational stage,
A, B – logarithmic function parameters, in this case, selected on the basis of backtracking.

The final result, in the form of superposed laboratory and numerical curves, is presented in Fig. 9.

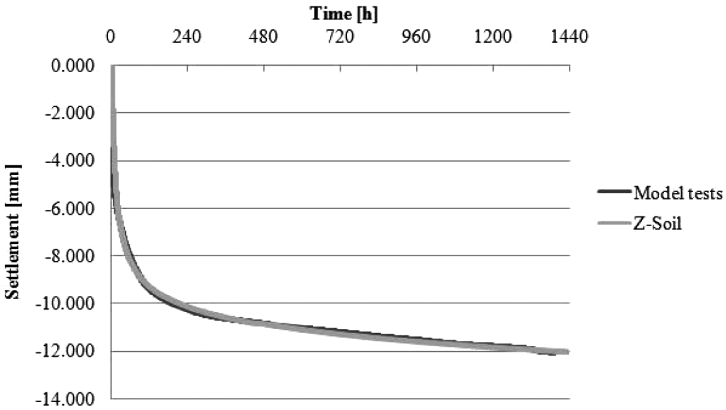


Fig. 9. Numerical and laboratory consolidation curves for the model without column

There are plans to perform a series of numerical analyses for systems with columns with the use of a numerical model calibrated in this way. The aim of such analyses will be to identify changes in horizontal and vertical filtration at every stage of the investigation.

5. Observations and conclusions

During the course of the research and the interpretations of the results, the author observed what follows and draws the following conclusions:

- In the described tests, no visible difference was observed in the course of the consolidation process of the column-weak soil system for the DR and VR columns. On the basis of small scale tests, can it be stated that the settlement value is determined by time, way of load placing, volume and density of drain material and not by the method of column formation. The author plans to conduct further research on a bigger scale that would permit drawing other conclusions.
- Investigations examining consolidation proved that the application of the DR and VR columns results in horizontal filtration occurring in the direction of the column. No quantitative conclusions could have been made due to the research scale which was too small. The similarity of the results for different models allowed only for qualitative conclusions.
- In similar investigations, insulation (e.g. using mineral wool) of the sides of the container in which tests are conducted should be considered. That would make laboratory conditions more similar to the conditions in situ, where the dynamic wave induced by the DR rammer drop may spread to long distances.
- Moisture tests showed only a little difference in consolidation of the two systems, which should be considered as negligible in designing. However, the analysis of processes occurring during the reinforcement construction clearly indicates tendencies to change.

– The importance of horizontal filtration was confirmed by differences in moisture values between the system without a column and two models with columns. Horizontal filtration will constitute the object of detailed analyses in future.
– The application of FEM allowed the identyfication of the processes occurring in the system without column during laboratory tests. The FEM software seems to be necessary to draw other conclusions from the investigations.

In further works, the author would like to find out what is the influence of the DR and VR column formation process on horizontal filtration in the vicinity of the column. The results of laboratory tests and numerical analyses for the DR column will be compared with analytical solutions which do not take into account the specificity of the DR method.

References

[1] Asalemi Ali Amini, *Application of seismic cone for characterization of ground improved by vibro-replacement*, PhD Thesis, Teheran 2006.

[2] Castro J., Sagaset C., *Consolidation around stone columns. Influence of kolumn deformation*, International Journal for Numerical and Analytical Methods in Geomechanics, 33, 2009, 851-877.

[3] Castro J., Sagaset C., *Deformation and consolidation around encased stone columns*, Geotextiles and Geomembranes 29, 2011, 268-276.

[4] Dheeerendra Babu M.R., Nayak S., Shivashankar R., *A critical review of construction, analysis and behaviour of stone columns*, Geotech Geol Eng, 2013, 1-22.

[5] Duncan J.M., Chang C.Y., *Nonlinear analysis of stress and strain in soils*, Journal of the Soil Mechanics and Foundations Division, ASCE, 96 (SM5), 1970, 1629-1653.

[6] Gryczmański M., *Methods of analyzing bearing capacity and settlements of soil strengthened with stone columns*, Inżynieria Morska i Geotechnika, Vol. 5, 1993, 224-231.

[7] Hughes J.M.O., Withers N.J., *Reinforcing of soft cohesive soils with stone columns*. Ground Engineering, Vol. 7, No. 3, 1974, 42-49.

[8] Kwiecień S., *Theoretical and experimental analysis of soil strengthening with the use of dynamic replacement method*, PhD Thesis, Politechnika Śląska, Gliwice 2008.

[9] Kwiecień S., Sękowski J., *Stone columns formed with dynamic replacement technology*, Monograph, Wydawnictwo Politechniki Śląskiej, Gliwice 2012.

[10] McCabe B.A., McNeil J.A., Black J.A., *Ground improvement using the vibro-stone column technique*, Paper presented at the Joint meeting of Engineers Ireland West Region and the Geotechnical Society of Ireland, NUI Galway, 15.03.2007, 1-12.

[11] Priebe H., *The design of vibro replacement*, Technical Paper – reprint from Ground Engineering, 1995.

[12] Sękowski J., Kwiecień S., *Dynamic replacement. Practical aspects of the use in roads engineering*, Magazyn Autostrady, Vol. 10, 2010, 24-128.

[13] Sękowski J., Grzesik B., *Consolidation of subsoil reinforced with dynamic stone columns – laboratory tests*, Roczniki Inżynierii Budowlanej – Zeszyt 8/2008, 67-70.

[14] Sękowski J., Grzesik B., *Influence of driven stone columns on water content of the strengthened subsoil*, Problemy geotechniczne i środowiskowe z uwzględnieniem podłoży ekspansywnych, Bydgoszcz 2009, 201-207.

[15] Sękowski J., Kwiecień S., Kanty P., *The influence of the rammed stone kolumn formation on strength parameters of the surrounding soil*, Budownictwo i Inżynieria Środowiska 4/2013, 301-308.
[16] Terzaghi K., *Erdbaumechanik auf Bodenphysikalischer Grundlager*, Deuticke Vienna, Austria 1925.
[17] Zimmermann Th., Truty A., Podleś K., *Z_Soil.PC 2009 Manual*.