Original research paper (Oryginalny artykuł naukowy)

DSc., PhD., Eng. Sławomir Kwiecień, prof. PŚ[1)*]
ORCID: 0000-0001-6401-2471
PhD., Eng. Siergey Ihnatov[1)]
ORCID: 0000-0002-5747-291X

Influence of the dynamic replacement technology on the shape of columns in laboratory conditions

Wpływ technologii wymiany dynamicznej na kształt kolumn w warunkach laboratoryjnych

DOI: 10.15199/33.2023.10.07

Abstract. The paper presents the results of laboratory tests on the influence of the dynamic replacement column formation technology, i.e. the depth of the initial crater, the height of its filling and the impact energy on the shape of the columns and their length. The tests were carried out at a stand enabling the observation of the driving process. The test results indicate the possibility of making the longest columns of optimal shape with the use of less energy with partial filling of the initial crater equal to the height of the pounder.

Keywords: dynamic replacement; geotechnical engineering; ground improvement; stone columns; soft soil.

Streszczenie. W artykule przedstawiono wyniki badań laboratoryjnych dotyczących wpływu technologii formowania kolumn wymiany dynamicznej, tj. głębokości wykonania krateru początkowego, wysokości jego zasypu oraz energii uderzenia na kształt kolumn i ich długość. Badania przeprowadzono na stanowisku umożliwiającym obserwację procesu wbijania. Wyniki badań wskazują na możliwość wykonywania najdłuższych kolumn o optymalnym kształcie z zastosowaniem niewielkiej energii przy częściowym zasypie krateru początkowego równego wysokości ubijaka.

Słowa kluczowe: wymiana dynamiczna; geoinżynieria; wzmocnienie podłoża; kolumny kamienne; grunt słaby.

Dynamic replacement [1-3] is one of the several dozens methods of soil improvement used in geoengineering [4] involving partial in depth replacement of soil [5]. During this process columns of non-cohesive soil with a sandy to stony fraction are formed and the technology itself seems relatively simple – it consists of dropping a heavy pounder on the surface of the ground forming a crater which is subsequently filled with column material. Successive drops of the compactor drives the material into the soil and after another crater is formed the steps are repeated. In the final stage of forming the columns sets of the pounder decreases and the soil uplift around the column increases [6, 7]. Based on the experience of the authors the length of thus formed column under field conditions does not normally exceed 4.5 m [8], although foreign experience mentions cases of formed columns of up to 9.0 m in length [9, 10]. Moreover the type of column (whether it is supported on a load bearing layer or floated) and it's shape play key role in load transfer properties of the column[8]. There is no direct influence on the length and diameter of the columns during its forming, in contrast to such methods as vibro-replacement [11] or 'Geopier' columns [12]. It is therefore justified to explore proper formation technology for such columns, i.e. proper determination of initial crater depth, height of its backfill and energy of the compacting blow in order to make, firstly, longer columns than previous experience allows, and secondly of desirable shape. This lead authors of the paper to conduct research in the matter under laboratory conditions reflecting process of dynamic replacement allowing for observation of column formation process.

[1)] Department of Geotechnics and Roads Silesian University of Technology
[*)] Correspondence address: slawomir.kwiecien@polsl.pl

Shape of the dynamic replacement columns and its influence on load transfer

Previous research performed by one of the authors, including survey of 65 dynamic replacement columns in situ, has shown that those can vary in shape and length, which affects the behaviour of loaded columns and the transfer of pressure to both the ground which is being reinforced and load bearing layer [8, 13].

Depending on geo- and hydrological conditions and technique of forming two groups of columns can be distinguished: those resting on load bearing layer with flat base and those floated in reinforced layer with hemispherical base [6, 13].

In the first group, based on thickness of the reinforced layer one can distinguish columns of the following shapes: cylindrical, inverted truncated cone and barrel-shaped with the largest diameter in the middle and lower part [6, 13].

Survey of the second group revealed columns which in shape were: cylindrical, with widened base and widened head.

Load tests of columns performed in the field as well as numerical analyses [8, 13] showed a clear effect of the shape and support of the columns on their load bearing capacity and stiffness. The greatest stiffness and capacity was observed for columns supported on the load bearing layer with flat base, especially if the diameter increased with depth (Fig. 1a). At the same time the columns with decreasing diameter (Fig. 1b) were characterized by the lowest load bearing capacity and stiffness. Hence it is desirable in practice to formthe columns of the first type with length greater than current practice based on experience (greater than 4.5 m). This may be possible with an appropriate choice of parameters: depth of initial crater, height (volume) of its backfill and impact energy used.

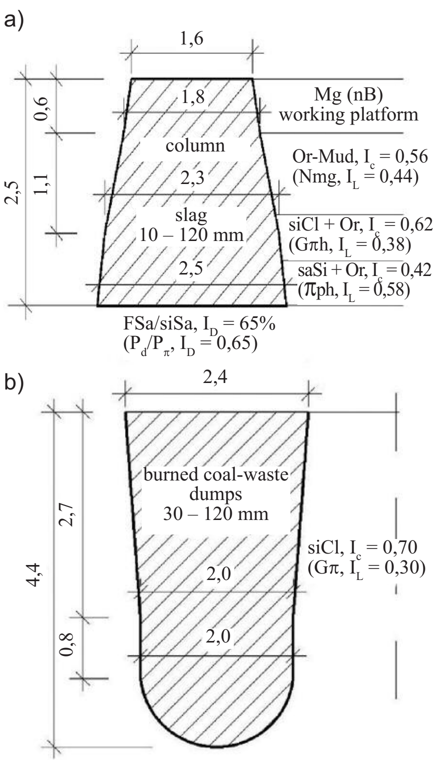

Fig. 1. Example of dynamic replacement columns shapes with extremely different load-bearing capacity and stiffness [6]
Rys. 1. Przykładowy kształt kolumn wymiany dynamicznej o skrajnie różnej nośności i sztywności [6]

Test stand and materials used

Test stand was arranged for observation of the process of forming the column in dynamic replacement technology. The study was performed in a cuboidal box with outside dimensions of 1.5 m (width) × 1.0 m (height) × 0.15 m (depth) with front panel made of acrylic glass (Fig. 2a). Thickness of the wooden walls of the box was 18 mm and the wall of acrylic glass 16 mm [14].

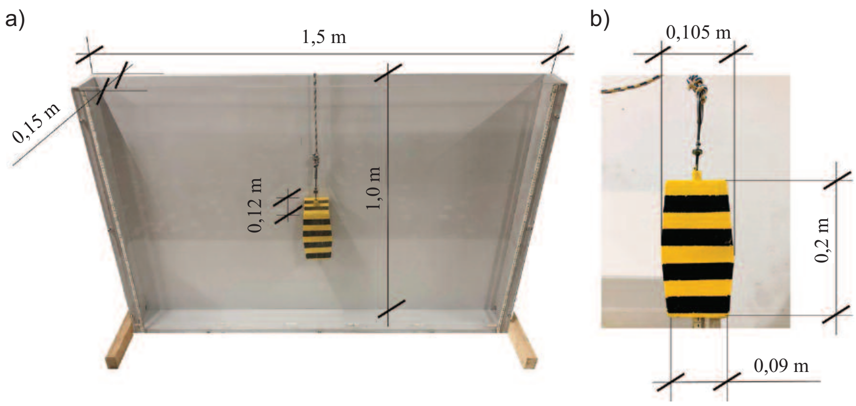

Fig. 2. Test stand (a) and the pounder (b) [14]
Rys. 2. Stanowisko badawcze (a) i ubijak (b) [14]

Dimensions of the pounder, granulation of the aggregate used for the columns and thickness of the reinforced layer were selected by adoption of geometric scale of 1:10 in relation to the real conditions.

Columns were formed with a barrel-shaped pounder (Fig. 2b), close in shape to ones used in real conditions, with the height of 200 mm (H_p), diameter in the middle of 105 mm (D_p) and with top and bottom width of 90 mm, thickness of 120 mm and mass of 11,02 kg. The pounder during drop moved inside closed square guide (Photo 1) which allowed for consistent drops from the height of 0.2 to 1.4 m [14].

Process of forming the columns was recorded using a camera with frame rate of 100 FPS. Photographic documentation of every stage of the study was also performed. Displacement analysis of aggregate in soft hydrogel was performed using GOM software [15]. Vectors of displacement paths of driven-material as well as resulting shapes were determined for every drop during forming of columns.

In case of ground improvement by the means of dynamic replacement usually three material zones can be distinguished. These are the weak subsoil, high strength and stiffness layer underlying the weak layer and the dynamically replaced columns. These zones were simulated in the test with different materials and soils. Bearing layer with height of 30 – 40 cm was formed of medium sand. Columns were formed of medium gravel (with grain size of 2 – 16 mm). The weak layer was modelled by using cross-linked acrylic polymer (p) mixed with water (w). Before establishing correct ratio of p/w, two-stage tests were performed, regarding transparency and strength of the mix. The first initial stage involved macro-

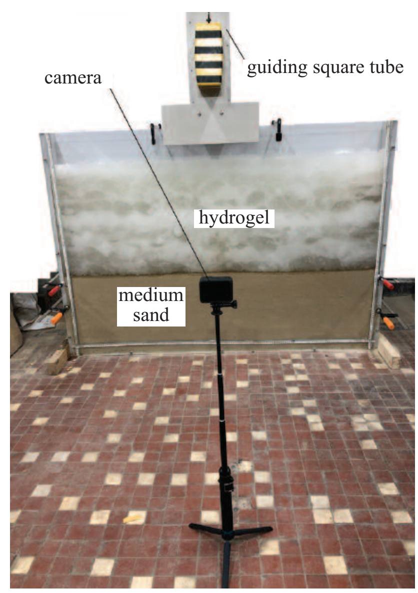

Photo 1. The test box before tests
Fot. 1. Stanowisko badawcze przed rozpoczęciem badań

scopic control of the mix behaviour when mixing hydrogel with water at ratios of 1 : 6, 1 : 8, 1 : 10, 1 : 15, 1 : 20 and 1 : 25. The second stage proper consisted of test loading of the selected mix on the test stand in the range of primary load of 0–285 Pa. The tests carried out showed that with the ratio (p/w) equal to 1: 15 (by weight) the resulting mix was of high transparency and soft state. In case of mix with p/w ratio <1: 15 it was hard to mix the polymer with water (rapid reaction with water and white inclusions of unbound polymer in the mixture). At the same time p/w ratio of >1: 15 resulted in liquid state of the hydrogel [14]. Analysis of the results of test loading and FEM computations performed (reverse analysis) showed that mechanical parameters of the chosen mixture were as follows: E = 7 kPa, ϕ = 0,4°, c = 75 Pa.

Before performing the actual tests the physical and mechanical parameters of the soils used were determined. These included the determination of grain size distribution (acc. to PN-EN ISO 17892-4:2017-01 [16]), minimum and maximum dry densities of the soil matrix (acc. to PN-88/B-04481 [17]), the specific density (acc. to PN-EN ISO 17892-3: 2016-03 [18]), strength parameters in direct shear test (acc. to PN-EN ISO 17892-10: 2019-01 [19]) and strain parameters in oedometer test (acc. to PN-EN ISO 17892-5: 2017-06 [20]).

Mechanical properties were determine for two different states of sand and gravel i.e. for minimum (ρ_{dmin}) and maximum dry density of the soil matrix (ρ_{dmax}).

The results of the material tests are presented in tables 1 and 2.

Table 1. Selected physical properties of the used soils
Tabela 1. Wybrane cechy fizyczne gruntów stosowanych w badaniach

Type of soil	Uniformity coeficient C_U	Coefficient of curvature C_S	Specific density ρ_s [t/m³]	Minimum dry density ρ_{dmin} [t/m³]	Maximum dry density ρ_{dmax} [t/m³]
Medium sand (MSa)	3,33	0,92	2,68	1,59	1,94
Medium gravel (MGr)	3,43	1,59	2,66	1,50	1,83

Table 2. Selected mechanical properties of the used soils
Tabela 2. Wybrane cechy mechaniczne gruntów stosowanych w badaniach

Type of soil/Dry density [t/m³]	Angle of internal friction ϕ [°]	Modulus of compression [MPa]:	
		primary*	secondary*
Medium sand (MSa) / 1,59	29,9	4,1 – 38,0	14,5 – 93,5
Medium sand (MSa) / 1,80	33,6	8,3 – 74,9	38,0 – 108,5
Medium gravel (MGr) / 1,53	36,1	6,2 – 44,8	93,3 – 124,1
Medium gravel (MGr) / 1,82	42,5	19,6 – 102,9	100,4 – 192,9

* first value from the interval of 25 – 50 kPa, second from: 400 – 800 kPa

The research programme

Previous experience with work on the test stand were included in the research programme [14]. The first phase of the study performed within the scope of the research project (no. SzN/I/33/DRPRO/2022), regarding the influence of the height of the reinforced layer on the shape of the dynamic replacement columns, showed that columns formed in a layer of hydrogel with height of 50 cm (the ratio of reinforced layer thickness (H_s) to the height of the pounder (H_p) was equal 2.5) formed with a hemispherical base and does not rest with whole cross-section on the load bearing layer but instead only rested in a single point (in the form of tangent to the circle) and therefore effectively formed a floating-column [14]. As previously mentioned this is not an optimal solution from the point of view of load transfer. It was therefore decided to continue tests in the hydrogel layer of the same height and determine how each of the mentioned technical parameters i. e. depth of the initial crater (H_k), height (volume) of its backfill and chosen impact energy influence the height and shape of columns.

Before the tests the load bearing layer in the stand was formed, simulated with medium sand, laid in layers compacted with hand tamper to the density index of I_D = 0.44. It's height was initially 0.4 m but after the first series of tests it was lowered to 0.3 m. The cause for that was the hydrogel leaving the test stand due to its displacement by the material of the column.

After forming the load bearing layer, the mixed hydrogel was put in layers on top of it. It's density was 1.01 t/m³.

Introducing of three types of columns (described as A, B and C type) was planned, for which the initial crater was of height: 0.2 m (type A, H_k/H_s = 0.2/0.5 = 0.4); 0.3 m (type B, H_k/H_s = 0.6) and 0.4 m (type C, H_k/H_s = 0.8). The crater was filled with gravel in 50% (columns A_50), 75% (columns B_75, C_75) and 100% (columns A_100, B_100, C_100). In case of partial backfill it was decided to increase the height of filling (from 50% to 75%) due to problems with crater wall stability in the soft hydrogel mix.

After full formation of each of the columns the material would be removed from the stand and the missing volume of hydrogel would be refilled.

3 test series were performed for each of the columns. A total of 18 columns were made (table 3).

Table 3. The research program
Tabela 3. Program badań

Type of column	Depth of the initial crater formed [m]	H_k/H_s [-]	Backfill of the crater [%]	Number of series[-]
A_100/A_50	0,2	0,4	100/50	3/3
B_100/B_75	0,3	0,6	100/75	3/3
C_100/C_75	0,4	0,8	100/75	3 / 3

Height of the drop for the pounder was 0.2 – 1.4 m and was determined individually, e.g. in case the drive of the pounder being too low the drop height would be increased and/or the backfill would not be introduced in this step. At the same time too large drive of the pounder resulted in lowering the drop height. A rule was adopted for the value of the pounder drives to be within a range of 75% to 125% of the pounder height (except in the case of the initial crater).

Test results

In the course of forming of type A column with full backfill of crater (A_100) the greatest vertical displacements are observed along its axis resulting in forming a semicircular base of the column (Photo 2a) which as a result of further impacts moves downwards and widens to the sides at the same time (Photo 2b). In the final stage of forming the column (Photo 2c) the greatest displacements are observed in the upper part of the column and fully formed it is pear-shaped resting in single point on the load bearing layer (Photo 2d).

In case of lower backfill rate (column A_50) in the first phase of the pounding the core of the column moves almost vertically to the load bearing layer (Photo 3a) and after reaching the top of the sand layer material of the column moves to the sides (Photo 3b) and with successive drops a flat base is formed (Photo 3c). As the result fully formed column is pear-shaped with a flat base (Photo 3d).

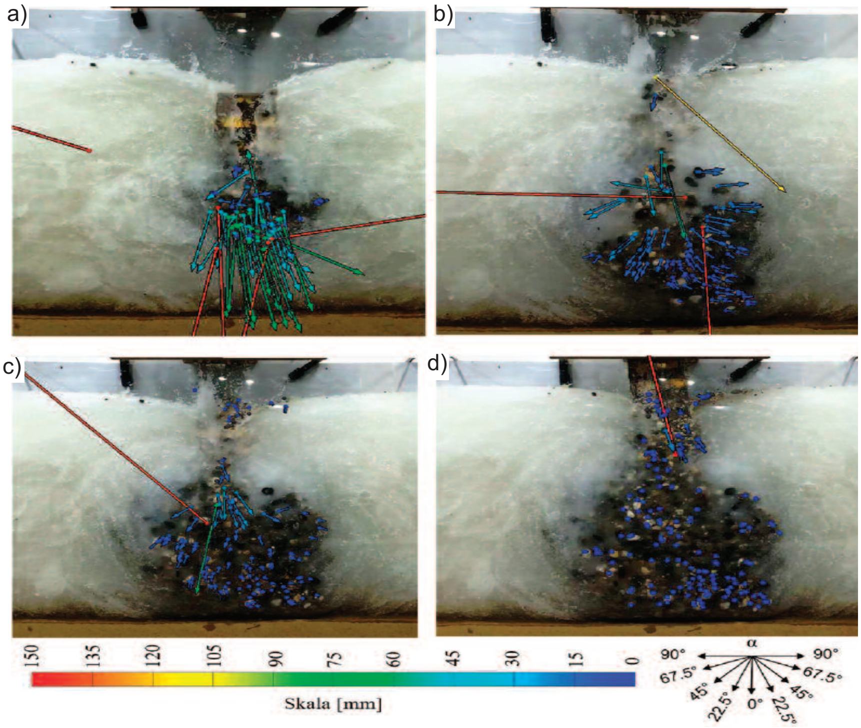

Photo 3. The vectors of the resultant displacements of the backfill material column type A with partial crater backfill (A_50), after pounder: a) 3rd drop; b) 12th drop; c) 20th drop, d) 28th drop (compaction of column head)

Fot. 3. Wektory przemieszczeń wypadkowych kolumny typu A przy częściowym zasypie krateru (A_50) po zrzucie ubijaka: a) 3.; b) 12.; c) 20.; d) 28. (dogęszczenie głowicy kolumny)

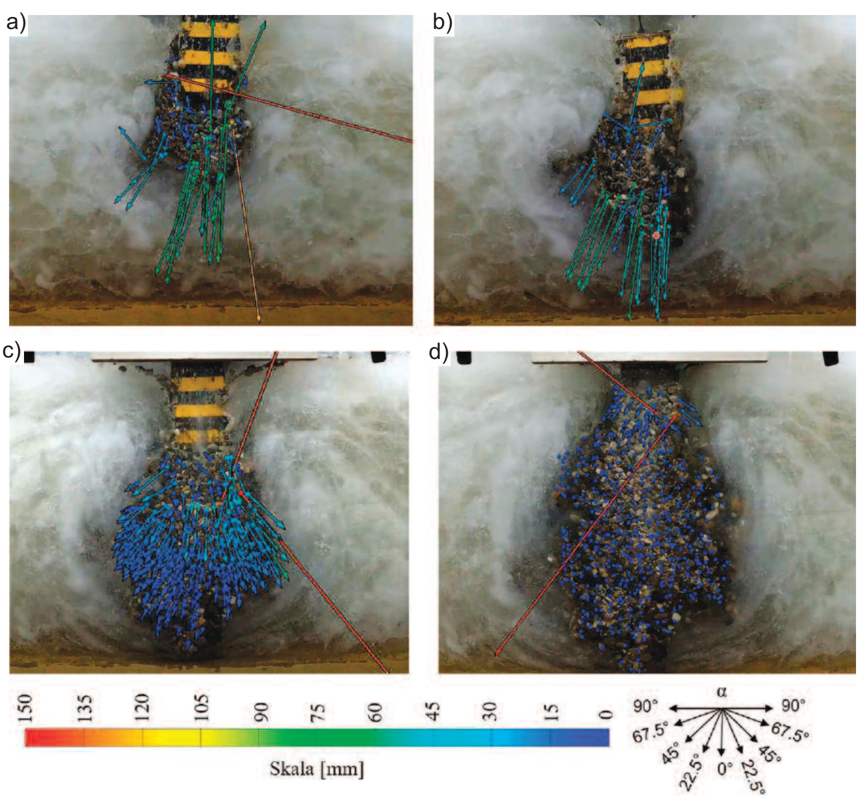

Photo 2. The vectors of the resultant displacements of the backfill material column type A with full crater backfill (A_100), after pounder: a) 1st drop; b) 4th drop; c) 10th drop, d) 15th drop (compaction of column head)

Fot. 2. Wektory przemieszczeń wypadkowych kolumny typu A przy pełnym zasypie krateru (A_100) po zrzucie ubijaka: a) 1.; b) 4.; c) 10.; d) 15. (dogęszczenie głowicy kolumny)

After producing the initial crater of type B column with its full backfill (B_100) from the start of forming of the column its core undergoes rotation (Photo 4a and 4b) and with successive drops the rotation increases to about 70°. Then the material driven in starts to move at the other side of the column as well (a shear forms in the upper part of the column core – Photo 4b and 4c). In the final stage the base of the column is irregular in shape and does not reach the load bearing layer. The core of the columns above the base holds roughly constant diameter and tapers down on top of the column (Photo 4d).

The use of partial backfill of the crater of the B type column (B_75) results in the initial phase of the pounding with vertical displacement of the material (Photo 5a) but before reaching the load bearing layer (Photo 5b) the core of the column rotates and with successive drops the rotation increases to about 70° (Photo 5c and 5d). Column material above the base starts to move in both directions and a discontinuity forms between the base and the core. The final shape is elongated pear-shape (Photo

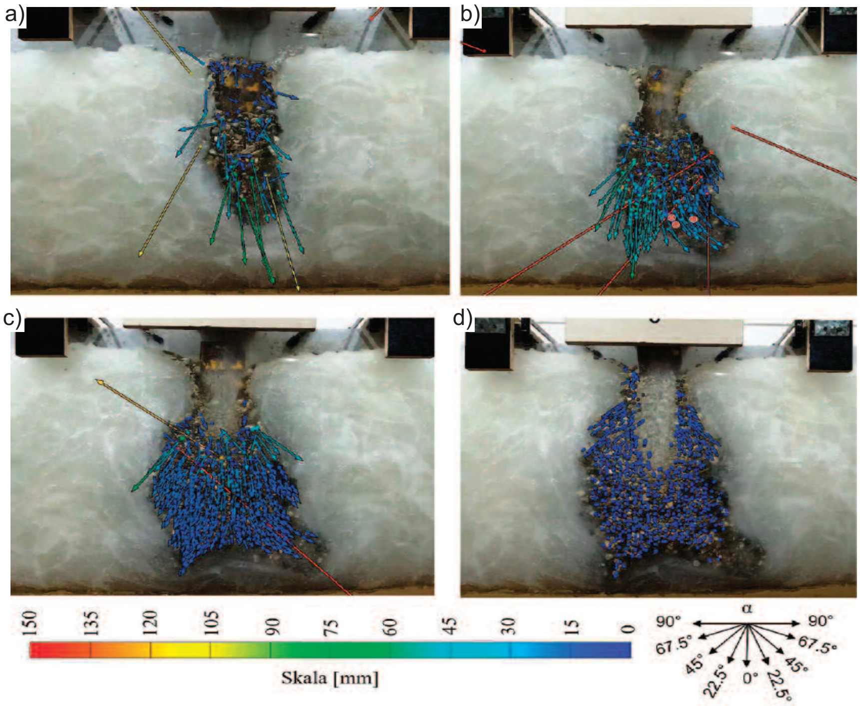

Photo 4. The vectors of the resultant displacements of the backfill material column type B with full crater backfill (B_100), after pounder: a) 1st drop; b) 4th drop; c) 9th drop, d) 14th drop (compaction of column head)

Fot. 4. Wektory przemieszczeń wypadkowych kolumny typu B przy pełnym zasypie krateru (B_100) po zrzucie ubijaka: a) 1.; b) 4.; c) 9.; d) 14 (dogęszczenie głowicy kolumny)

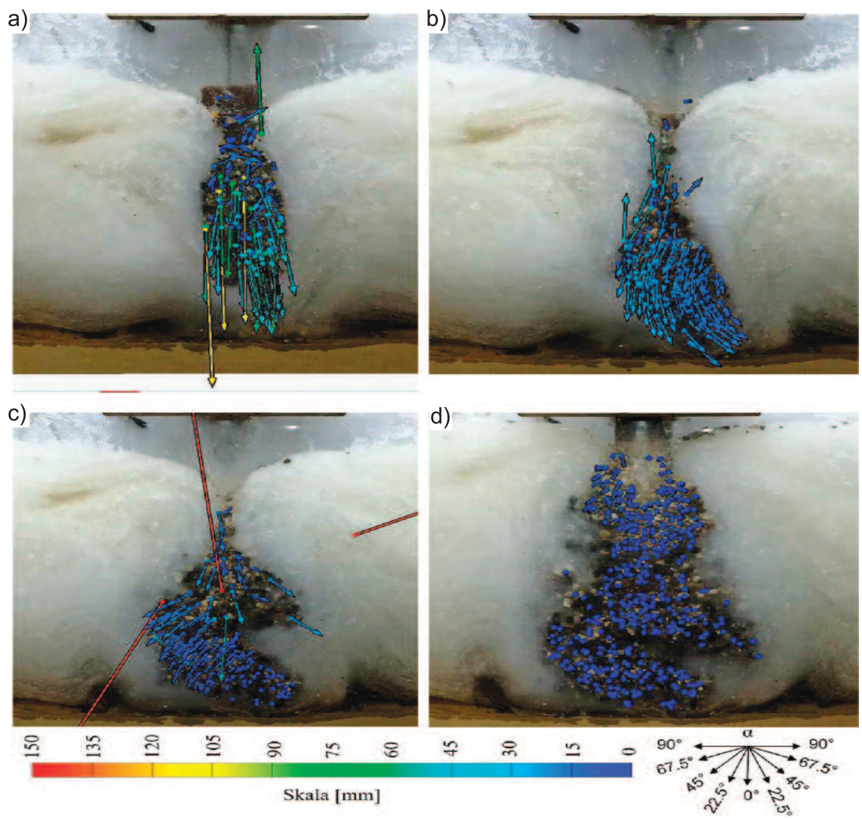

Photo 5. The vectors of the resultant displacements of the backfill material column type B with partial crater backfill (B_75), after pounder: a) 1st drop; b) 4th drop; c) 12th drop; d) 25th drop (compaction of column head)

Fot. 5. Wektory przemieszczeń wypadkowych kolumny typu B przy częściowym zasypie krateru (B_75) po zrzucie ubijaka: a) 1.; b) 4.; c) 12.; d) 25. (dogęszczenie głowicy kolumny)

5d) with single-point support on the load bearing layer.

In case of producing a crater with the largest depth (type C) and with full backfill (C_100) after the initial vertical displacement of the core of the column (Photo 6a) and before reaching the top of the load bearing layer the core widens at the top (aggregate spreading to both sides) and rotates at the bottom (Photo 6b). With further drops the rotation at the bottom of the core increases and at the top keeps spreading to the sides (Photo 6c) which results with the column only reaching the load bearing layer in one point (Photo 6d). Resulting column has irregular shape (Photo 6d).

Similar behaviour of the type C column material during pounding can be observed in case of partial backfill of the crater (C_75) and the column diameter is lower than type C_100 due to shorter rotating core (Photo 7a-d).

Value of impact energy used in column formation calculated as the product of drop height, pounder mass and gravitational force divided by the surface area of the pounder base and the amount of the gravel used in forming the column are presented on Fig. 3 and 4.

Analysis of the research results and conclusions

Adoption of different depths while forming the initial crater and percentage of the backfill have influence on necessary impact energy, volume of necessary aggregate and as a result on the shape of the columns

The highest initial drop energy of the pounder is needed in case of the fully backfilled craters that are meeting the condition $H^k/H_s = 0.6$ and 0.8 (columns B_100 i C_100 respectively) – Fig. 3. The reason for this is the necessity for breaking through the weak layer located underneath the forming column in order for it to sink deeper – the deeper is the backfilled initial crater, the lower are stresses at the base of the crater for the same drop height of the pounder. Lower values of impact energy caused by excessive drive of the dropped pounder were observed for the columns with lower backfill of the crater (A_50, B_75, C_75) and for the fully backfilled

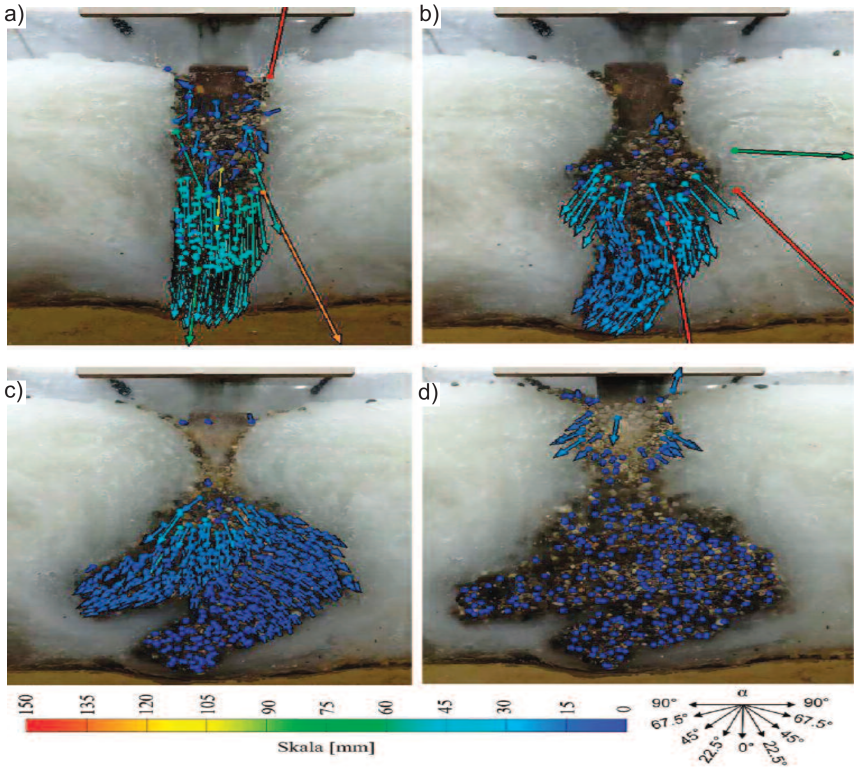

Photo 6. The vectors of the resultant displacements of the backfill material column type B with full crater backfill (C_100), after pounder: a) 1st drop; b) 3th drop; c) 12th drop; d) 23th drop (compaction of column head)

Fot. 6. Wektory przemieszczeń wypadkowych kolumny typu C przy pełnym zasypie krateru (C_100) po zrzucie ubijaka: a) 1.; b) 3.; c) 12.; d) 23. (dogęszczenie głowicy kolumny)

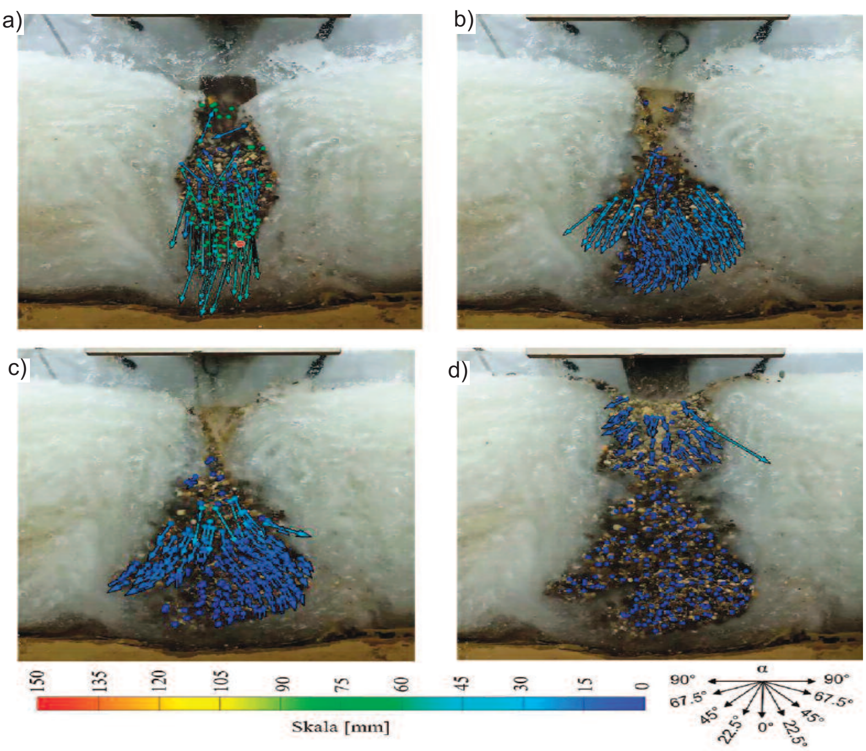

Photo 7. The vectors of the resultant displacements of the backfill material column type C with partial crater backfill (C_75), after pounder: a) 1st drop; b) 4th drop; c) 10th drop; d) 16th drop (compaction of column head)

Fot. 7. Wektory przemieszczeń kolumny typu C przy częściowym zasypie krateru (C_75) po zrzucie ubijaka: a) 1.; b) 4.; c) 10.; d) 16. (dogęszczenie głowicy kolumny)

crater (H_k/H_s = 0.6, column A_100), while the lowest value was observed for the column A_50.

Lower backfill of the crater for the columns A_50 and B_75 results with larger number of pounder drops, although from lower height but with larger total impact energy than when full backfill is performed (Fig. 3).

With increase of the initial crater depth increases also total volume of aggregate used for the column (Fig. 4). For the two most extreme cases the mass of the aggregate of the column B_75 is 50% larger than the mass of aggregate of the column A_50. Increased aggregate requirement for the B and C type columns is caused by attempting to form continuous core column with a flat base after column core undergoes rotation. Also in this case the material is sheared in the upper part of the column core and subsequently introduced material is dislodged to one or both sides excessively increasing the diameter of the column and volume of the necessary material.

The most desirable case, from the point of view of load transfer is forming the column with flat bottom resting on the load bearing layer and with the continuous core widening with depth. These requirements are true for column A_50 with initial crater which satisfied the condition H_k/H_s = 0.4 and was 50% backfilled. With the full backfill of the crater (A_100) the widening core was also formed but its base was only resting on the load bearing layer in one point. The widened base of aforementioned column effectively reduces the core penetration into the layer needing improvement. At the same time adoption of deeper, fully or partially backfilled initial craters (B and C type columns), due to greater slenderness of the initial core than A type columns, is increasing the probability of the rotation in the core and formation of the columns only partially resting on the load bearing layer (all B and C cases) and with discontinued core (B and C with the exception of B_75). In the in situ conditions the probability of the core rotation is increased by the fact that impacts of the pounder might be offset

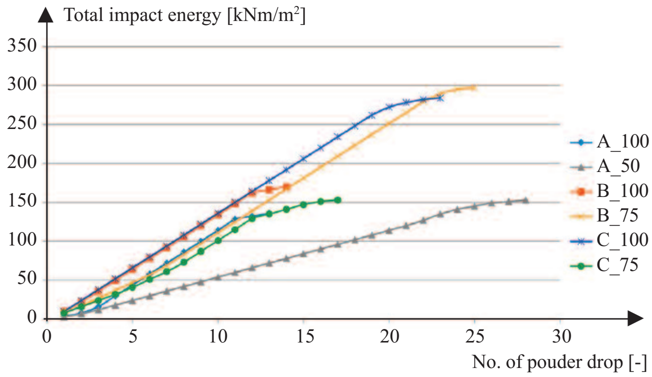

Fig. 3. Impact energy used in columns formation
Rys. 3. Energia uderzenia stosowana przy formowaniu kolumn

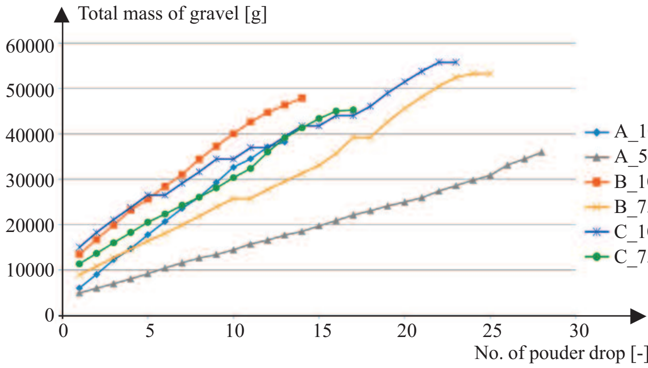

Fig. 4. Mass of gravel used in columns formation
Rys. 4. Masa żwiru zastosowanego przy formowaniu kolumn

from the axis of the forming core (in the process of forming the column the crane must put the pounder aside repeatedly while the crater is being backfilled), Furthermore with decreasing distance of the column base to the load bearing layer the influence of the latter increases, lowering the penetration rate of the base into the improved layer [13].

The shape of the formed type A_100 columns is the same as in case of previous research [14].

The most noticeable fact is that the column of optimal shape (A_50) was formed using the slowest increase of impact energy (pounder dropped from the lowest height) and using the smallest amount of the aggregate. In practice this could mean that using lower performance equipment, with the proper formation and backfill of the crater it is possible to produce a column resting on the load bearing layer with diameter increasing with depth.

The research performed did not include testing influence of the state of the reinforced layer or the shape of the pounder on the technique of forming the columns – these could be direction for further research in the laboratory and/or in the field.

The authors are aware of the qualitative nature of the research, which is heavily influenced, among other things, by the effect of scale or the possibility of aggregate spreading in only two dimensions (this resulted e.g. in increased column diameters in the observed plane). Nevertheless, these results are the basis for carrying out tests in a natural scale, for soils of low strength and stiffness (e.g. peats) and subsequently developing guidelines for the technique of dynamic replacement columns.

Bibliography

[1] Hamidi B. Distinguished ground improvement projects by dynamic compaction or dynamic replacement. Ph. D. Thesis, Curtin University. 2014.

[2] Gryczmański M. Wzmacnianie podłoża wbijanymi kolumnami kamiennymi. Przegląd doświadczeń śląskich. Inżynieria i Budownictwo. 2003; 3: 123 – 126.

[3] Kłosiński B. Wzmacnianie podłoża słupami tłuczniowymi formowanymi metodą ubijania. Inżynieria Morska i Geotechnika. 1992; 3: 171 – 173.

[4] Pisarczyk S. Geoinżynieria. Metody modyfikacji podłoża gruntowego. Warszawa: Oficyna Wydawnicza Politechniki Warszawskiej. 2020.

[5] Gryczmański M. Dynamiczne metody wzmacniania podłoża gruntowego. XVI Ogólnopolskie warsztaty pracy projektanta konstrukcji. Ustroń, 2001; 2: 41 – 57.

[6] Kwiecień S. Wzmacnianie podłoża gruntowego metodą wymiany dynamicznej. Materiały Budowlane. 2023. DOI: .

[7] Kanty P. Analiza doświadczalna wpływu wymiany dynamicznej gruntu na otoczenie. Praca doktorska. Gliwice; 2014.

[8] Kwiecień S. Odkształcalność kolumn wymiany dynamicznej ustalana na podstawie próbnych obciążeń. Gliwice: Wydawnictwo Politechniki Śląskiej; 2019.

[9] Chu J, Varaksin S, Klotz U. Mengé P.: Construction Processes. State of the Art Report. Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering. Alexandria. 2009: 3006 – 3135.

[10] Guo J, Wang R, Yang Z, Zhu C. Mucky clay treatment by dynamic compacted gravel column method. Rock and Soil Mechanics. 1993; 14; 2: 61 – 74.

[11] Castro J. Modeling stone columns. Materials. 2017; 10 (7): 782, 1 – 23.

[12] Razeghi HR, Niroumand B, Ghiassian H. A field study of the behavior of small-scale single rammed aggregate piers, testing methodology and interpretation. Scientia Iranica. 2011; 18 (6): 1198 – 1206.

[13] Kwiecień S. Influence of Load Plates Diameters, Shapes of Columns and Columns Spacing on Results of Load Plate Tests of Columns Formed by Dynamic Replacement. Sensors, 2021; DOI: 10.3390/s21144868.

[14] Kwiecień S., Ihnatov S., Kowalska M. Influence of soft layer thickness on the aggregate displacement in the backfill material of dynamic replacement columns – results of laboratory model tests. Archives of Civil Engineering. 2023; DOI: 10.24425/ace.2023.146079.

[15] Jasiński R, Stebel K, Domin J. Application of the DIC Technique to Remote Control of the Hydraulic Load System. Remote Sensing. 2020; https://doi.org/10.3390/rs12213667.

[16] PN-EN ISO 17892-4:2017-01 Rozpoznanie i badania geotechniczne – Badania laboratoryjne gruntów – Część 4: Badanie uziarnienia gruntów. 2017.

[17] PN-88/B-04481 Grunty budowlane. Badania próbek gruntu. 1988.

[18] PN-EN ISO 17892-3:2016-03 Rozpoznanie i badania geotechniczne – Badania laboratoryjne gruntów – Część 3: Badanie gęstości właściwej. 2016.

[19] PN-EN ISO 17892-10:2019-01 Rozpoznanie i badania geotechniczne – Badania laboratoryjne gruntów – Część 10: Badania w aparacie bezpośredniego ścinania. 2019.

[20] PN-EN ISO 17892-5:2017-06 Rozpoznanie i badania geotechniczne – Badania laboratoryjne gruntów – Część 5: Badanie edometryczne gruntów. PKN. 2017.

Funding: This work was supported by the Polish National Centre for Research and Development (Narodowe Centrum Badań i Rozwoju), "Solidarity with scientists" programme [grant No.: SzN/I/33/DRPRO/2022, Experimental analysis of the formation process of dynamic replacement columns under laboratory conditions].

Accepted for publications: 02.10.2023 r.