Rigid inclusion ground improvements as an alternative to pile foundation

Bernadetta Polańska¹ and Jakub Rainer¹,²

¹ Wroclaw University of Science and Technology, Faculty of Civil Engineering, Wyb. Wyspiańskiego 27, 50-370 Wroclaw, Poland
² SM POLSKA Sp. z o.o. S.K., Szlachecka 13, 32-080 Brzezie, Poland

E-mail: 233466@student.pwr.edu.pl

Abstract: The new buildings are very often planted in places where the soil is weak or unbearable. Their occurrence eliminates the possibility of shallow foundation. In such cases, it is necessary to make the ground stronger or to make a deep foundation. The paper presents a comparison of the method of the soil reinforcement with rigid concrete columns and deep foundation on piles. Features that combine both methods are presented, as well as advantages and disadvantages of both methods. The next part of the paper describes the basic calculation methods of the subsoil reinforcement with concrete columns. The work is finished with a case study describing an object located in southern Poland, where originally designed foundation piles in CFA technology were replaced by rigid columns made in the same technology.

1. Introduction

Today's buildings are faced with a number of demands and requirements. One of the most important is to preserve the safety of the structure and the safety of use [1]. Nowadays, there is often an additional economic criterion, which is related with the willingness to minimize construction costs and time of its realization by the investor or contractor. Meeting the above conditions is accompanied by the participants of the investment process at each stage of works, for example when choosing the method of building foundation.

Due to the increasingly dense development of the cities, investors have less and less options to locate their investments. This limitation often forces them to choose a location within the area of weak or unbearable grounds. In order to properly design the foundation it is necessary to carefully analyse the ground on which the investment is planned to be located [2]. In the process of performing the soil investigations, which may be boreholes or CPT sounding, layers in the soil profile are separated and basic mechanical and strength parameters are determined for further design [3]. The results of the soil tests start procedure to determine the optimal type of foundation. Based on these results and on the knowledge of the construction, the designer can propose the most effective solution in terms of safety, technology and economy. A shallow foundation is considered first, as it is the cheapest and the simplest in technology. If the designer finds that the foundation does not satisfy the ultimate or serviceability limit states, and further increases in the dimensions of the foot or strip foundation will not achieve the required effects or are uneconomic, then other solutions are chosen. The most common method in such a case is deep foundation on piles [4, 5]. They allow to transfer forces from the structure to deeper layers of bearing soil that must be identified in course of ground investigations [6].
As we usually assume that piles carry 100% of load applied, a careful analysis of their capacity is recommended with regard to soil variability and pile length [7]. Recently, following the recommendations from Eurocode 7 Part 1 [3], deep foundation design is more and more based on information acquired directly from various field testing of pile’s capacity [8, 9]. Such procedure, despite the fact that deep foundations keep usually a safety margin provided by the subsoil, may also lead to overestimation of single pile capacity due to often extrapolation of testing results [10].

The reinforcement of the ground with rigid concrete columns [11], which has become very popular in recent years [12-15], may be considered as an alternative to deep foundation. It allows for more economic and faster construction of building objects, while keeping the assumed requirements for both: Ultimate Limit State (ULS) [16, 17] and Serviceability Limit State (SLS) [17-21].

2. Differences in the behaviour of the pile and column
As it was previously mentioned, deep foundation on piles provides the transfer of loads to the deeper bearing layers, through separate structural elements such as the foundation piles. The piles may be loaded with both tensile (if reinforced) and compressive stresses. Piles may also transmit lateral forces, depending on their bending capacity and stiffness. The axial capacity of pile in compression consists of the load bearing capacity of its base and shaft [3, 4]. In the case of a tension pile, its capacity is equal to capacity of its shaft only.

Reinforcement of the ground by means of rigid inclusions consists in the introduction of elements of much greater rigidity into the weak ground. These elements are called columns and may be made using the same technologies as piles (prefabricated, CFA, FDP, DSM, etc.). In this way, a soil-concrete composite material is created in which both the column and the soil surrounding it are the supporting elements. The surrounding soil is considered as a material with a rigidity of an order of magnitude smaller than that of the column, which is able to transfer part of the stresses. The basic differences between the behaviour of columns and piles are shown in figure 1.

![Figure 1. Differences in the behavior of the pile (a) and column (b)](image)

As can be seen in the figure 1, the column is an element of lower size than a pile. This is due to the assumption that with pile foundations 100% of the load is transferred to the pile. In the case of columns, it is assumed that part of the load is transferred through the ground thus the inclusions take over from about 50% to even 95% of the stresses. The columns are more flexible elements and are usually finished in a bearing layer of less than 1m because in order to mobilise the soil the column system should settle otherwise the columns will take up almost all of the load and their behaviour will be almost identical to the piles. In addition, in the case of pile foundations, there are regulations [4] that specify the minimum length of anchoring in the bearing layer. The column, as opposed to a pile, does not have to be structurally bonded to the foundation. A common practice is to make the transmission layer of non-cohesive material between the pile head and the foundation [11].
Furthermore, in the situations where only vertical loads are transferred to the foundation the columns can be made as concrete elements without reinforcement which is not possible with piles due to the existing legislation and minimum reinforcement requirements [1]. However, if bending moments are expected to occur in the designed column only at a short distance from the column head, it is possible to use the reinforcement only in the given section. The concrete strength class for piles is usually specified by the exposure class [1]. In the case of unreinforced columns, the concrete class can be determined by the stresses in the inclusion.

The above-mentioned reasons may indicate the advantages and superiority of reinforcing the ground with rigid columns over deep foundations. Correctly designed and properly constructed column strengthening may result in significant savings of money and time.

Due to the complexity and complication of their behaviour rigid inclusions are characterised by an increased risk of failure. The failure probability is additionally increased by errors in recognition therefore designing this type of solution requires more attention and considerable experience in designing and performing specialist geotechnical works.

3. Calculation methods for the ground improvement with rigid concrete columns
Solving problems related to rigid inclusion ground improvements can be obtained using analytical and numerical methods. Both methods are discussed briefly below.

3.1. Analytical methods
Analytical methods are the simplest way to solve typical problems. In these cases usually there is a regular grid of columns and because of this it is not required to use numerical methods. The result of the calculations is the estimation of load distribution on the ground and column, as well as settlement values in the dimension of a single periodical cell, and then taking into consideration the behaviour of the elementary cell in the group.

An essential aspect of the analytical methods is to obtain the correlation between the settlement of the column in the bearing soil and the load. This curve is a sensitive part of analytical methods, because currently the only method that allows to determine the settling - load relationship with a small error is the static test load [8, 10].

It is possible to define this curve based, among other things, on CPT tests or transformation formulas, but the possibility of making significant errors cannot be ignored [7, 17].

![Figure 2. Negative skin friction diagram [3]](image1)

![Figure 3. Simplified subgrade reaction coefficient distribution [3]](image2)
The procedure of determining load distribution has an iterative character. First of all, in the case of foundation slabs based on the ground improved with columns, it is assumed that 100% of the loads coming from the building are taken over by the columns \(Q_p\) and the load of the surrounding ground \(q_0\) is equal to zero. Then from the settlement-load curve of the column the value of settling which is caused by a given force is derived. Under the influence of the settlement of the column, the foundation slab starts to exert pressure on the ground surface. This results in the ground settlement causing negative friction in the upper part of the column head marked as \(F_n\) which decreases as the depth increases (figure 2).

At a certain depth marked as \(h_c\) on figure 2 the value of displacement of the column and the surrounding soil becomes identical. It means that the negative friction at the side of the column will disappear. At depths greater than \(h_c\), the load on the surrounding weak soil causes an increase in horizontal stress, which results in an increase in positive friction and an increase in the column bearing capacity.

In order to determine the load distribution, it is necessary to estimate the negative friction value, additional vertical loads from the ground friction at the column side, as well as additional pressures on the ground under foundation slab. In further iteration steps, the load is transferred from the column to the ground. The procedure should be terminated when the increase of load on the surrounding ground \(\Delta q_0\) is equal to 0 with the acceptable assumed error [11].

Another widely used analytical method is to model the improved substrate with concrete columns as an elastic medium of non-homogeneous vertical stiffness (figure 3). According to the figure 3, within the range of the column, the ground is modelled using the parameter of elasticity \(k_i\), and in the other areas using the parameter \(k_s\). The range of column interaction can be determined using the cone method [11] if some transmission layer of \(H_m\) thickness is provided. If the foundation slab is placed directly on the column heads, the range of column interaction covers only the area with the radius equal to the column radius. Then the area prepared in this way is solved using typical calculation software from the field of structural mechanics.

Both methods are described in detail in ASIRI guidelines [11].

3.2. Numerical methods
Numerical methods are used everywhere where, due to the complexity of the task, it is impossible to solve equations describing the problem in an analytical way. They are suitable for solving problems with complicated geometry, varied loads or complex geology. Their application requires a lot of experience and engineering intuition. Among the numerical methods one can distinguish 2D and 3D issues.

The analysis of issues in 3D spatial structure allows for full modelling of the section or the whole area covered by the improvement, so it may be considered that they best represent the actual work of the structure. The biggest disadvantage of this type of issues is the complex process of modelling and significant calculation time, often counted in days.

In order to reduce calculation time, 3D is simplified and modelled in 2D in a plane strain state. For this transition, the 2D model has to be calibrated. This is due to the fact that in 3D issues, the columns are volumetric or beam elements with the dimensions as they really are. In a flat state of deformation, the elements which appear to be flat and orthogonal to the cross-sectional plane have an infinite dimension. Thus, beam elements in 3D, become disc elements in PSS. Without proper calibration, this replacement causes significant distortion in the results. In order to avoid this effect, before modelling the whole object in 2D, it is necessary to perform the calculation in the dimension of a single elementary cell in 3D by loading the column with a certain force.

Then model the single periodical cell in 2D and by manipulating the disc width and the parameters of the contact elements, aim to match the load-settling curves under a given force. Then an element with calibrated parameters may be used to model the whole task. After correct calibration, 2D and 3D results should not differ significantly.
4. Analysis of an example
The analysed investment is located in southern Poland. Typical hydro-geological conditions of the area covered by the investment are presented in figure 4, and the basic parameters are presented in table 1. At about 6 m depth, there are cohesive soils in the form of silt clay and silt. These soils have very varied parameters and in places they should be considered as non-bearing. Below them there are deposited various medium grained sands, which can be classified as bearing. Very cohesive clay is deposited beneath them from a depth of about 12 m, which also qualify as bearing sands.

Table 1. Table of the soil parameters

| Strata number | Ground name     | Liquidity index $I_L$ [-] | Density index $I_D$ [-] | Internal friction angle $\phi$ [$^\circ$] | Undrained shear strength $c_u$ [kPa] | Oedometric modulus $M_0$ [kPa] |
|---------------|-----------------|---------------------------|-------------------------|------------------------------------------|-----------------------------------|--------------------------------|
| Ia            | Silt / Silty clay | 0.70                      | -                       | 7.0                                      | 6.0                               | 10000                          |
| Ib            | Silt / Silty clay | 0.47                      | -                       | 11.0                                     | 10.0                              | 16000                          |
| Ic            | Silt             | 0.16                      | -                       | 15.5                                     | 18.0                              | 32000                          |
| IIa           | Fine sand        | -                         | 0.50                    | 30.5                                     | -                                 | 62000                          |
| IIb           | Medium sand      | -                         | 0.55                    | 33.5                                     | -                                 | 103000                         |
| III           | Clay             | 0.10                      | -                       | 11.5                                     | 55.0                              | 31000                          |

Figure 4. Hydro-geological conditions

The object of the development is a residential multi-family building with an underground garage. The building has 8 floors above ground and 1 underground storey. The structural support has been designed as a reinforced concrete structure consisting of walls and a frame made of vertical columns and horizontal beams. The building was originally designed on a 70 cm thick slab and in places where the columns are located the slab was thickened to 90 cm due to the possibility of punching.
A shallow foundation was originally designed however the building did not meet the serviceability limit states as the settlements exceeded 10 cm (figure 5.b). As the first possible solution, an deep foundation on CFA piles with a diameter of 60 cm was adopted. This solution made it possible to fulfil the requirements for the foundation in EC7 [7] concerning serviceability and load capacity. The piles started at the bottom of the slab, i.e. about 240 m above sea level and were 11\text{–}13 m long. The piles were reinforced due to minimum reinforcement and were fixed to the slab [6]. A general list of works and materials is presented in table 2.

![Figure 5. a) Settlement of the building with rigid inclusion ground improvements b) Settlement of the building on a shallow foundation](image)

At the realization phase it was decided to change the method of foundation from an deep foundation on CFA piles to improvement of the ground with rigid concrete columns in the same technology. This solution allowed, by employing the soil under the slab and surrounding columns to transfer loads, to limit settlements to an acceptable level (figure 5a). Moreover, costs were reduced by shortening the time of works and the amount of used material. A detailed material list of the solution is presented in table 2. The change of the calculation approach allowed to reduce the time of investment execution by several days. The material savings were significant because the columns were unreinforced, contrary to the original solution and the total number of linear metres of the columns was 25% less than the piles.
Table 2. Solution materials’ list

| Deep foundation | Soil improvement |
|-----------------|------------------|
| Technology      | CFA              | CFA              |
| Diameter        | 600mm            | 600mm            |
| Length          | from 11 m to 13 m| from 8 m to 9 m  |
| Number of pieces| 224              | 224              |
| Total length    | 2582 m           | 1921 m           |
| Concrete strength class | C30/37 | C20/25 |

5. Conclusions

The improvement of the soil with rigid inclusions has become more and more popular in the recent years. A significant advantage of using this method is that considerable material savings are possible in relation to the deep foundations on piles. Although the pile and column forming technologies are the same, the specificity of the soil activity is different. In the approach in which an object is founded on piles, weak soil is ideally identified with non-bearing material. In the approach with columns, weak soil is seen as a medium in which its stiffness and deformability are important parameters influencing the effectiveness of the whole solution of ground improvement.

Rigid columns should not be identified with piles, therefore the methods of solving problems with columns are different from those of piles. These methods are briefly presented and discussed in Chapter 3. Extracted from the French ASIRI guidelines [1], they are one of the most popular and widely used methods in the engineering community. The main differences between deep pile foundation and substrate improvement with rigid columns are summarised in table 3 below.

Table 3. Comparison of pile and column behaviour

| Feature                         | Deep foundation                  | Soil improvement with rigid inclusions |
|---------------------------------|----------------------------------|---------------------------------------|
| Bearing element                 | Pile                             | Column + surrounding soil              |
| Stiffness                       | Stiffness of the pile to limit settlement. | The stiffness of the columns is designed to take advantage of the resistance of the soil. |
|                                 | Settlement of piles considered as an unfavourable effect | Column settlement as a phenomenon activating the soil to transfer part of the loads |
| Necessity of reinforcement      | According to EC2 [6], the minimum reinforcement required | Reinforcement due to internal forces. |
|                                 | Allowable non-reinforced components |                                       |
| Connection to the building structure | Required                        | Not required                           |
| Concrete strength choice        | The main influence on the concrete strength class is the aggressiveness of the environment | The main influence on the concrete strength class is the stress value in the column core |
| Length of fixing in the bearing layer | Minimum length of fixing required in accordance with the standard [5] | Length determined in terms of load capacity or rigidity |
| Static test loads               | Required [5]                     | Not required                           |

The analysis of the presented case confirms the thesis that the improvement of the ground by means of rigid inclusions is a proper alternative to deep foundation, allowing to achieve significant benefits only by changing the calculation approach to those taking into account the positive impact of the improved medium. In the analysed case, the saving reached up to 30%, the savings reached even more than 20% of the total cost of the original version of the pile foundation.
Acknowledgements
Special thanks are addressed to SM Polska Sp. z o.o. S.K. for providing materials to describe the case study presented above.

References
[1] PN-EN 1992-1 Eurocode 2: Design of concrete structures- Part 1: General rules and rules for building
[2] PN-EN 1997-2 Eurocode 7: Geotechnical design- Part 2: Ground investigation and testing
[3] PN-EN 1997-1 Eurocode 7: Geotechnical design- Part 1: General rules
[4] PN-83/B-02482, Foundations: Bearing capacity of piles and pile foundations (in Polish)
[5] Bustamante M and Gianesselli L 1982 Pile bearing capacity prediction by means of static penetrometer CPT. Proc 2nd European Symp. On Penetration Testing, Amsterdam, 493-499
[6] Bagińska I, Baca M, Różański A and Sobótka M 2013 Verification of pile capacity determined on the basis of CPTu. Przegląd Komunikacyjny, 3, 26-31 (in Polish)
[7] Wyjadłowski M, Bagińska I and Rainer J 2018 Probabilistic assessment of pile capacity based on CPTu probing including random pile foundation depth. MATEC Web Conf., 196, 01058
[8] Rybak J 2017 Some remarks on foundation pile testing procedures. IOP Conf. Ser.: Mat. Sci. Eng., 245 (2), 022092
[9] Sobala D and Tkaczynski G 2017 Interesting developments in testing methods applied to foundation piles. IOP Conf. Ser.: Mat. Sci. Eng., 245 (2), 022074
[10] Rybak J and Król M 2018 Limitations and risk related to static capacity testing of piles. MATEC Web Conf., 146, 02006
[11] ASIRI National Project: Recommendations for design, construction and control of rig inclusion ground improvements. 1st edition, 2012
[12] Bernuy C, Hor B, Kim S, Song M and Alqoud S Y 2018 LNG tanks on rigid inclusions: Kuwait. Innovative Infrastructure Solutions, 3 (1), 80
[13] Kraemer S R, Condon R B and Wissmann K 2018 Rigid Inclusion System Supports Multi-Story Residential and Parking Garage Structures in Organic Soil Profile. Geotechnical Practice Publication, 2018-March (GPP 11), 370-379
[14] Cacciola D V, Siddiqui S I, Ramp S and Ahmed F 2018 Rigid Inclusion Supported Embankments for New Jersey Turnpike Interchange 14A: A Case Study. Geotechnical Special Publication, 2018-March(GSP 298), 94-108
[15] Mazzei D, Kniss K, Elsaïd F and Zhang Y 2019 Rigid inclusions ground improvement for a new energy facility: Design, construction, and full-scale embankment load testing and results. Geotechnical Special Publication, 2019-March (GSP 309), 101-114
[16] Dalak D 2015 Load transfer platform designing according to the ASIRI recommendations, Inżynieria Morska i Geotechnika, 4, 608-612 (in Polish)
[17] Kozubal J, Wyjadłowski M and Steshenko D 2019 Probabilistic analysis of a concrete column in an aggressive soil environment. PLoS ONE, 14 (3), e0212902
[18] Stefaniuk D 2013 Determination of settlements of foundations located on vertically reinforced subsoil: the comparison of H. and P. methods. Prace Studentów Politechniki Wrocławskiej. Konferencje, 18, 256-261
[19] Pham H V, Briançon L, Dias D and Racinais J 2019 Investigation of behavior of footings over rigid inclusion-reinforced soft soil: Experimental and numerical approaches. Canadian Geotechnical Journal, 56 (12), 1940-1952
[20] Wang D., Sánchez M and Briand J-L 2019 Numerical study on the effect of rigid inclusions on existing railroads. International Journal for Numerical and Analytical Methods in Geomechanics, 43 (18), 2772-2796
[21] Lődör K and Móczár B 2020 Design and modelling process of soil improvement with concrete strengthening elements. Periodica Polytechnica Civil Engineering. 64 (1), 287-295