AUTOMATION IN MICROPILE DESIGN

Maciej Szczygielski[1], Natalia Maca[2]

ABSTRACT

The paper presents a comprehensive 3D finite difference parametric study, based on Python scripts, on the performance of micropile groups and networks and investigates the effect of the geometric variables on the final geometry (limit state ratio) and cost of the foundation structure. In particular, the paper presents the modular, script-based approach to the numerical modeling which allows a high level of automatization of the process. Further, the authors show how Python scripts can be used in the numerical modelling of micropiles, parameterized foundation size, and micropile geometry for variant analysis and ways to report the results. Also, a direction for further study on micropile network design is indicated.

1. INTRODUCTION

Micropiles have been widely used for underpinning, as well as new foundations, in difficult geotechnical conditions or specific earth retention applications. Due to the efficiency of installation, they can be arranged in a wide range of geometrical configurations and work as an irregular root structure, optimized to precisely resist a given set of loads. However, the available analytical models are based on simplified static analysis, give only rough approximations, and do not describe fully the complex behavior of micropile groups or grillages, mostly because of the difficulties in description of such sophisticated 3D geometrical structures with conventional analytical methods. In the meantime, expectations from designers are not only safe, reliable structures, but also the optimized and most economical solution.

Currently, numerical modelling with advanced constitutive models for soil, and various types of structural elements of any geometrical complexity, gives satisfactory results in the context of correct definition of soil structure interaction, and seems to be the most reliable way of designing micropile foundations. Nevertheless, the large number of different input parameters and the time-consuming modelling process make it problematic to implement those methods in everyday use, especially when investigating several options. One way of overcoming these difficulties is an application of the parameterized algorithmic approach to numerical modelling.

This paper presents a comprehensive 3D finite difference parametric study on the performance of micropile groups, and investigates the effect of the geometric variables on the bearing capacity and displacements of the micropile foundation. In particular, the paper shows how Python scripts can be used in the numerical modelling of micropiles. As authors we believe these features all together can be a significant help to reach the full potential in the analysis of micropile foundations. Furthermore, it is hoped that the

[1] MSc. Eng., TITAN POLSKA Sp. z o.o., Milkowskiego 3/801, 30-349 Krakow, maciej.szczygielski@titan.com.pl

[2] MSc. Eng., TITAN POLSKA Sp. z o.o., Milkowskiego 3/801, 30-349 Krakow, natalia.maca@titan.com.pl

presented approach and scripts could support building better micropile design methods and promote micropile community development.

2. MICROPILE FOUNDATION DESIGN

2.1 General information

Micropiles developed by Dr. Fernando Lizzi were used for the first time in Italy in 1952 and, since then, the technology has been improved and is now used widely all over the world. Nowadays they are applied successfully for underpinning as well as new foundations in difficult geotechnical conditions, confined spaces or for specific earth retention applications (landslide stabilization). Extensive literature on this subject has beenwritten, e.g Lizzi (1985), Bustamante and Doix (1985), Ostermayer (1996), and some research programmes have been carried out e.g. FOREVER (Juran, 2003), giving us a good understanding of the behaviour of micropiled structures.

On the other hand, up to now, there is no widely accepted method, or specific design standard, for micropile design. Some design requirements are given by **EN** 14199 and several design guidelines, e.g. German DIN 1054:200. Also, some national industry studies, such as German EA Pfähle (DGGT, 2014) or American FHWA (FHWA, 2005) are helpful, but only regarding the single micropile or some of the aspects of group effects. The design of the complex behaviour of a group or network of micropiles is still down to the decision of the individual designer.

2.2 Single micropile

The design principles of a single micropile are in accordance with the general theory of the limit state analysis. The pile resistance, as geotechnical capacity, can be determined on the basis of empirical data, in which the characteristic micropile resistance at the ultimate limit state is determined based on the skin friction. The value of the skin friction is provided in standards, regulations, recommendations or in contractor's guidelines and depends mostly on the installation technology, in particular on the method and pressure of the injection. However, there is general agreement that the most rational way to proceed is to determine these parameters from measurements taken during a load test.

It should be noted that, under axial compressive load, the behavior of a micropile is mainly governed by the shaft friction mobilized at the soil-pile interface, while the tip resistance is negligible (it is estimated as 15-20% of the shaft friction (Bustamante, 1985)).

Structural design of the micropiles (reinforcement) depends on its type, but generally the procedure is well known and does not differ substantially from that for standard piles or general concrete-steel structures (as described in Eurocodes 2).

2.3 Groups

The ease with which the inclined micropiles can be installed makes it possible to produce spatial systems in order to transfer horizontal forces to the ground. The piles can be arranged in such a way that they work mainly on axial forces, even if lateral loads are applied to the foundation. This type of structure may be defined as a group or network of micropiles. A group of micropiles includes a number of vertical micropiles, sometimes with the exterior micropiles slightly inclined outwards.

To date little knowledge is available concerning the bearing capacity and settlement of the micropile groups. Existing design recommendations in EA-pfähle or FHWA guidelines are based on observations from driven pile groups, and do not take into account any resistance from the pile cap, i.e. a very conservative approach. The idea that piles in a group have a lower bearing capacity than a single pile is repeated in many works. Such a phenomenon may theoretically occur in extreme conditions, i.e. very small spacing of micropiles and poor base, which in practice is very rarely the case (Kłosiński, 2014).

In the case of micropiles, it was found in the FOREVER research program that interaction within the group has a positive effect on its load-bearing capacity and reduces settlement. It was shown that, in contrast to traditional friction piles, the highest load capacity groups of micro piles were obtained at spacing of 2.5 to 3.5D. Even in micropile groups with spacing of 7D, the load capacity was larger than single micropiles. The research also showed that when groups of micro piles were topped with a ground-bearing pile cap, the bearing capacity of the composite foundation was greater than the sum of the capacity of the groups of micro piles and that of the pile cap itself.

The parameters that seem to have the most influence on the behavior of groups of micropiles under vertical and horizontal loading were:

- number and arrangement of the micropiles
- micropile spacing
- influence of the pile cap (its shape and connection with micropiles)
- installation technique

This positive group effect is most likely due to "soil confinement' between the micropiles. Unfortunately, it is not possible to precisely quantify the contribution to the group effect of any chosen parameter, even though some studies suggest that this can be done. The group effects are also not easy to quantify because of the pile cap which carries a part of the load. Some analytical and numerical solutions were developed in FOREVER (Juran,2003), based on the hybrid models using the methods of load transfer functions for the axial loads (mobilization curves for the axial shaft friction, *t-z)* and the lateral loads (mobilization curves for the lateral reaction, *p-y)* and introducing the group effect through correction factors, but it has not been widely used.

2.4 Networks

Nevertheless, the main challenge in the design is to dimension the foundation as a network of micropiles. Such systems comprise multiple vertical and inclined micropiles interlocked in a three-dimensional network. A specific network is the "reticulated" foundation, formed in situ from soil reinforced with closely spaced raking and vertical micropiles.

As with groups of micropiles, the experimental and theoretical research carried out on micropile networks is rare, and little is known about their behavior. However, it was demonstrated on simple networks in FOREVER (Juran, 2003), that a specific mechanism inherent to inclined micropiles exists under vertical loading, i.e. the start of a progressive mobilization of the "lateral passive" reaction of the soil on the micropiles. Thus, the mechanism of a "lateral passive" reaction of the soil with the micropiles can yield, for large displacements and in certain conditions (density of the soil, relative soil-micropile stiffness, etc.), an improved bearing capacity of the network in comparison to that of an equivalent group. It also appears that a micropile network, regardless of the number of micropiles, provides a better behavior under horizontal loading than a similar group.

The design of a network of reticulated micropiles differs significantly from that of an individual micropile or a group of micropiles. The behavior of the network is conditioned not only by the factors defined for groups, but it depends significantly on the orientation of the micropiles in a network as characterized by:

- angle of the micropile inclination with respect to the vertical;
- interlocking angle of the direction of the micropile in a horizontal plane.

With regard to design, up to now no method of calculation for micropile networks has been proposed, except for simple networks. However, some development of load transfer functions with group effect factors and the homogenization methods are available (Juran, 2003).

2.5 Design of the groups and networks

The group and the network are problematic, firstly in the way of assessing the load on a single micropile from various combinations of load, and also in the aspect of the resistance of the whole group and its individual elements. However, it is the group effect what is the actual challenge in design, and up to now it has not been possible to reproduce this using popular standard analytical or empirical, or simple numerical, calculation methods. Also due to the limits of the most common design tools, the calculation of complex load combinations and optimization of the construction (in the sense of micropile arrangements influencing strongly the global behavior of the foundation) is almost impossible.

It seems that only 3D numerical tools, in which the pile element can be modelled and well calibrated, can take into account the specific characteristics of the network behaviour. Also, thanks to the implementation of parameterization and automation procedures in different numerical modelling software, design of the most reliable and economically optimized structure becomes more realistic.

2 NUMERICAL MODELLING WITH PYTHON SCRIPTING

2.1 Framework general description.

Design of geotechnical structures is based on many variables, especially when using numerical modelling software. Different soil conditions and geometry makes every project unique, but still repeatable actions can be found and replaced with scripts or macros. When using numerical modelling software one way of doing that is through an implemented programming interface, and for a number of major geotechnical software distributors (Itasca FLAC, Plaxis, ZSoil), Python is the programming language of choice. With its vast open library of scientific packages and extensions for data analysis, Python is a powerful tool for pre-processing, controlling the solver, and post-processing the numerical analysis results. The most common applications are for assigning soil parameters and layers, parameterizing the geometry of a model, or to control the stages of calculations. In this paper, the authors present the framework for micropile foundation modelling with use of Python scripts.

To automate the numerical modelling of Titan micropiles, a simple object-orientated library was developed in Python. Two basics object were defined: the *micropile* object and the *micropile group* object. Then a group of methods was written for generating, importing, exporting and modifying given objects. Information about a designed pile group can be imported from, and exported into, Excel spreadsheets, dxf drawings, and numerical model structural elements, and all geometrical and structural information can be generated and modified in the Python console. Combined with information about the soil conditions, the framework also calculates a micropile length according to the Lizzi Method. The attributes and structure of objects are presented on Figure 1.

Objects		Object atribiutes		
		geometrical	structural	calculated
Micropile =	[id,	x0, y0, z0, αxy, αz, length,	type, drill diameter, pile head, free length,	axial force, shear force]
Micropile_group =	[micropile_1, micropile_2, micropile_3, …., micropile_n]			

Figure 1. Structure of objects and their attributes used in automation script

Geometrical attributes of micropiles are the starting point coordinates, *αxy* angle, which is the direction angle in the horizontal plane (corresponding to the interlocking angle}, *αz* direction angle in the vertical plane, and the length of micropile. Structural attributes describe the technological aspects of micropile where the “type of the micropile” corresponds with TITAN micropile types, and in the group "calculated attribute”, forces in the micropile are assigned. Every attribute can be overwritten for one micropile object, or for all objects in a micropile group.

The implemented algorithmic approach allows an analysis to be conducted for a large number of variants. Results are exported in the form of a csv file, for ease of comparison, and for further processing, for example for CAD file generation.

2.2 Numerical interpretation of micropile structure

In this study micropiles are modeled as structural elements which are a one dimensional beam-type element with the predefined interaction with surrounding continuum in the normal and shear directions. Thus, each pile structural element is defined by its geometric, material (including the ability to specify a limiting plastic moment) and coupling-spring properties. The coupling springs are nonlinear, spring-slider connectors located at the nodal points along the pile axis that transfer forces and motion between the pile and the grid at the pile nodes (fig. 2) In addition, end-bearing effects can also be modeled, although usually for micropiles this is not used.

The shear and normal behavior of the pile-grid interface is cohesive and frictional in nature. The shear characteristics are modeled by defining coupling spring properties: stiffness, cohesive strength, friction angle and exposed perimeter. The interface in the normal direction is modeled as a spring-slider system. Its behavior during relative shear displacement is described numerically by stiffness, cohesive strength, friction angle, and exposed perimeter. The behavior of the normal coupling springs includes the ability to model load reversal and the formation of a gap between the pile and the grid.

The mechanical behavior of the couplers is depicted in terms of these parameters, as well as the effective confining stress (FLAC3D, 2019).

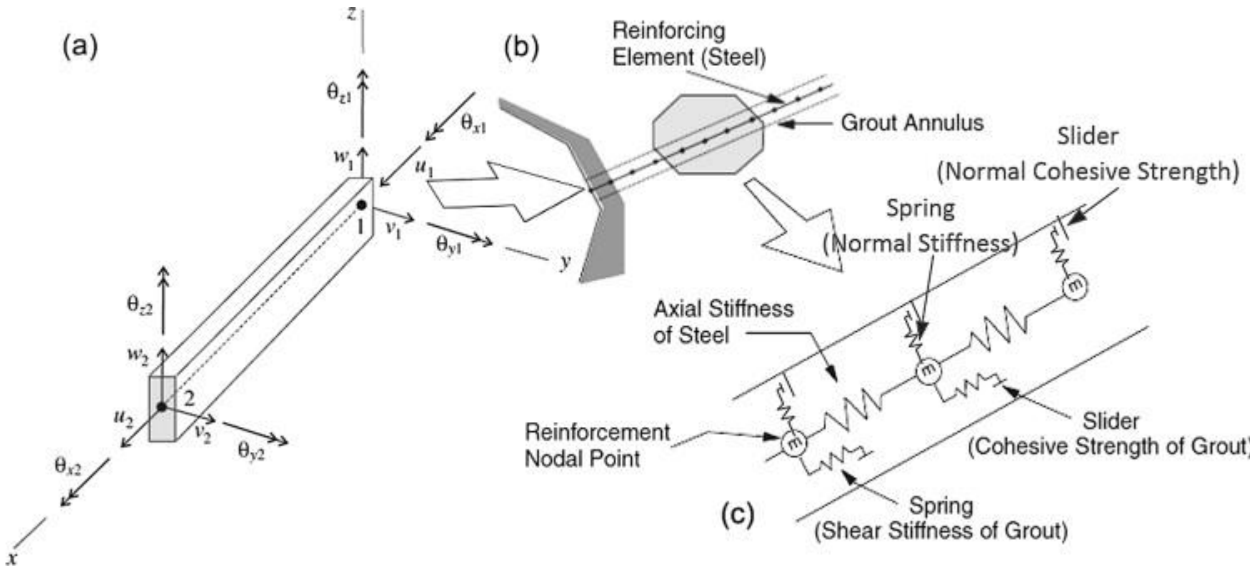
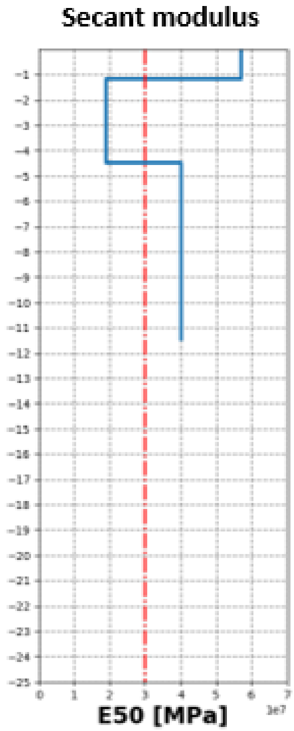


Figure 2. The pile structural element representation in FLAC3D: (a) beam element, (b) nodal division and (c) interaction parameters (Oke et al. 2014)

3 PARAMETRIC STUDY

3.1 Problem statement

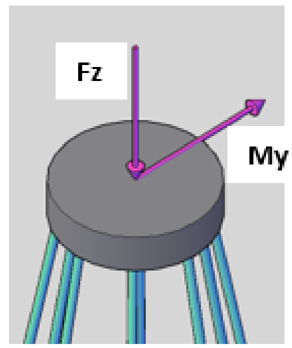
Spread footings of circular shape with various diameters, as well as micropile groups and network structures, were analysed as foundations in order to find the most reliable and economic solution in given set of boundary conditions. The crucial part of the study was the parametric analysis, investigating the influence of the geometry of the micropile group or micropile network on its resistance, and the difference between the micropile group and the network behavior. The foundation was subjected to vertical forces and moments acting on a horizontal plane, in various directions. Loads and geotechnical conditions selected for the analyses are shown below (fig. 3).



Soil parameters

Layer name	Depth	Density	Cohesion	Friction	Secant modulus E50	qsk
	m	kg/m3	kPa	deg	MPa	kPa
Rp2	1.17	1850	0	39	57	150
Gz2	3.3	2050	10	25	13	50
Gz3	7	2175	12	30	40	100

Loading case



Fz = 0.4 MN
My = 3.68 MN

Figure 3. Soil parameters and loading case

Numerical modeling software FLAC3D with micropile Python library developed in TITAN POLSKA engineering office was used in the analysis. It fits with the general design methodology introduced in the company, oriented to provide an efficient, highly automated, computational engine able to perform numerous parametric studies in order to find an optimized solution.

3.2 Description of the numerical model

Calculations were performed with Itasca FLAC3D software, a three-dimensional explicit Lagrangian finite-difference program for engineering mechanics computation, targeted at geotechnical analysis. The following parts of a numerical model of the foundation can be specified:

- Elements simulating soil – hexahedral elements with a Plastic Hardening constitutive model assigned,
- Elements simulating foundations – hexahedral elements with an Elastic constitutive model assigned for concrete and two dimensional shell elements to simulate the reinforcement.
- Elements between soil and foundation – two dimensional interface elements with Mohr-Coulomb failure criterion,
- Micropile simulating elements – one dimensional structural elements, with axial, lateral and bending resistance.

Parameters of the soil were assigned based on the geotechnical investigation. For the foundation elastic parameters of steel and concrete were used, while a friction angle of 20° was assigned for interface elements between the foundation and soil. For the micropiles, TITAN geometrical and material parameters were applied. No additional effect of the ground strengthening similar to observed soil confinement or lateral pressure mobilization was simulated. The base model geometry is shown in figure 4.

Because of the variable character of the moment vector direction, and axially symmetric geometry of the micropile group or network, it was assumed that, for the single load case, the maximum forces in one micropile should be considered for all micropiles.

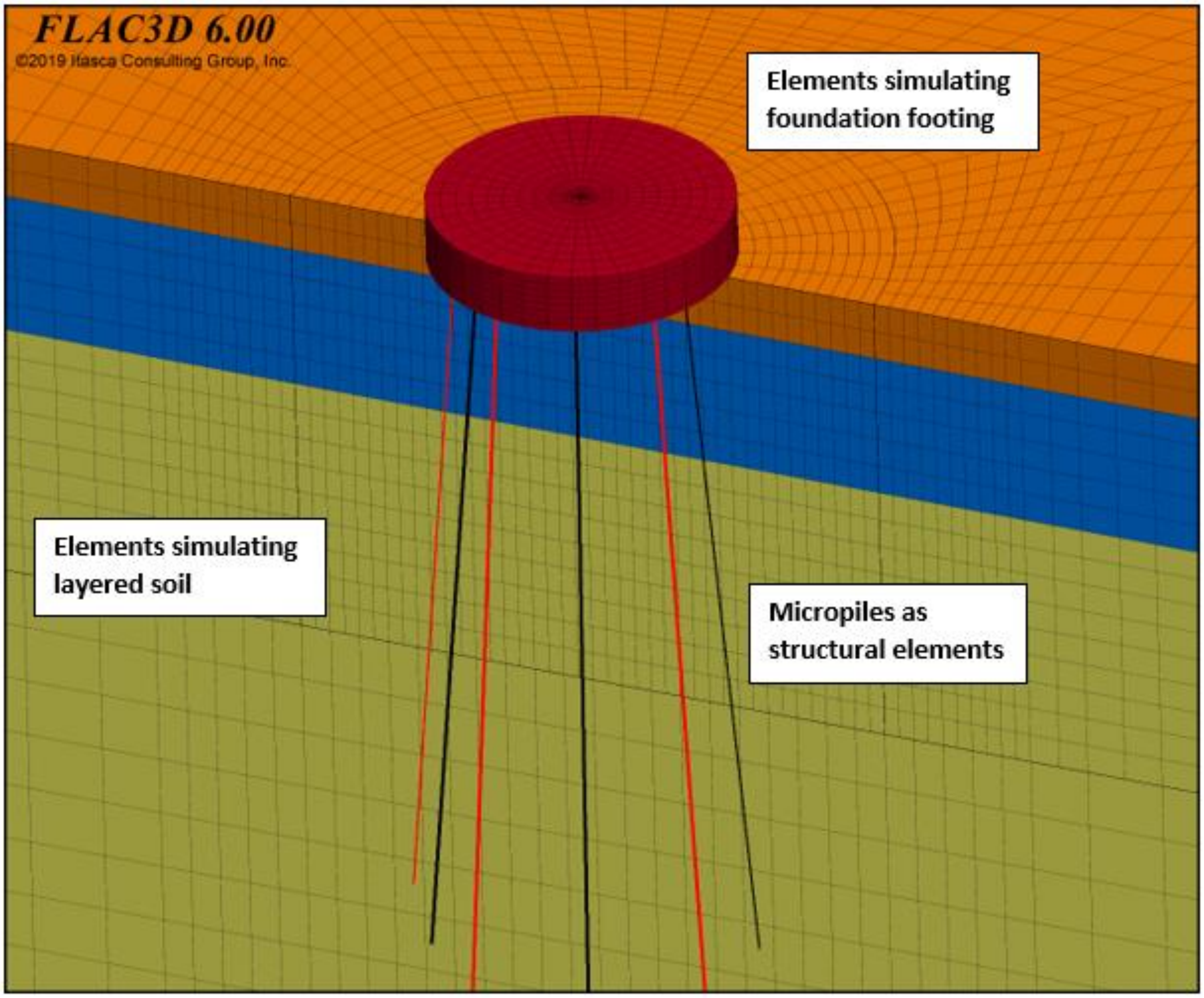


Figure 4. The base foundation model

The model was defined in script form, with separate modules for geometry generation, initial stress state assessment, micropile generation and applying forces to the foundation. Model dimensions and micropile geometry were determined based on the diameter of the footing. Micropiles were generated with Python functions. This form of numerical model definition eases automation and an algorithmic approach for the parametric study, the analysis process of which is described in next paragraph.

3.3 Algorithmic approach

The parametric study was performed in two stages. The aim of the first stage was to find the best combination of pile cap diameter and pile number for the foundation in the form of a simple group. The numerical model was solved for three different pile cap diameters: 3.6, 4.8, and 6 m. The lateral boundaries were extended automatically relative to the pile cap size to minimize the boundary effects. The micropiles were formed in a single circumferential order, with a 10 degree rake in the direction to the outside. Pile caps of diameter 3.6 m with 8 and 12 micropiles were solved, while for the diameter of 4.8 m models with 8, 10, 12, 16 micropiles were used, and for the diameter of 6 m models with 10 and 12 micropiles were used. All together in the first stage 8 combinations were analysed.

In order to find the optimal pile cap diameter and pile number, the total pile length and type had to be acquired for each combination. One calculation cycle started with the initial guess of the type and length of micropiles; then forces in the pile group were acquired from numerical analysis; then the pile length and type were finalised according to the given forces and soil conditions. The process was then iteratively repeated for each new pile length and type, until there were no changes in the geometry in the two latest iterations. For each combination there were an average of 5 iterations. In summary, for the first stage of the modeIling, 40 different calculations where carried out.

In the second stage, the network geometry of micropiles was investigated for the most optimal combination chosen in the previous calculations. Micropiles were divided into two groups (pilegroup1, pilegroup2), and the attributes of these two groups were modified separately. With this approach, a large variety of proposed geometrical configurations could be efficiently generated. In this stage, the parametric study was focused on the geometric aspects of the network: micropile arrangement, inclination and interlocking angle and their influence of the overall resistance and settlement of the foundation. Finally, 52 different combinations of the geometry were checked in the second stage of the analysis in order to find the one with the lowest axial forces in the micropile group.

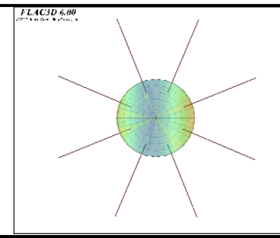
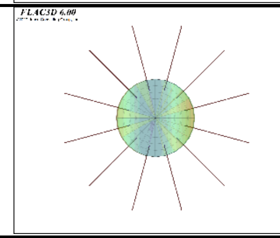
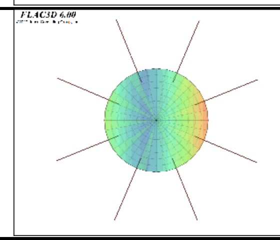
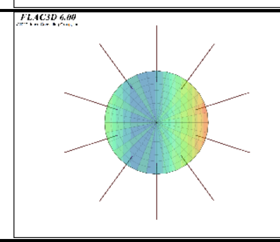
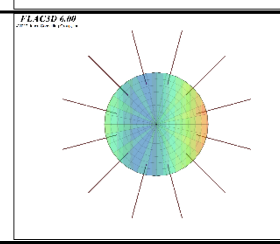
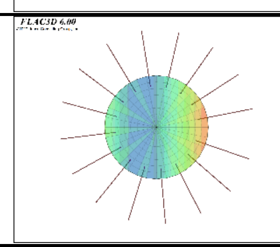
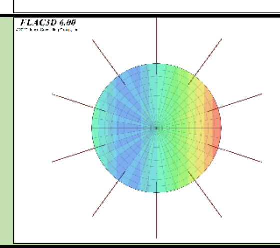
3.4 Stage I – micropile group results

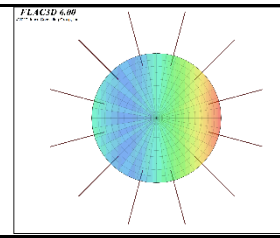
Results of the first stage of the analysis are shown in the table below (Table 1). As could be expected, generally with increasing pile cap diameter the loading on the single micropiles shows that the smaller micropile type could be used, and smaller settlements are observed. The deviations from this rule resulted mostly from the abrupt variability of the TITAN micropiles parameters. Differences in stiffness between two types is relatively higher than the difference in their load carrying capacity.

For the further calculation the combination with a pile cap of 6 meter diameter and 10 micropiles was used, as the total micropile length and micropile type for that combination were the most optimal and economical solution.

Table 1. Results of stage one analysis – micropile group

footing diameter	micropiles number	micropil e length	maximum footing disp.	TITAN micropile type	Total micropile length	
[m]	[]	[m]	[m]		[m]	

3.6	8	21	1.27E-02	73/53	168	
3.6	12	18	1.32E-02	52/26	216	
4.8	8	18	9.15E-03	52/26	144	
4.8	10	15	7.20E-03	52/26	150	
4.8	12	15	8.10E-03	40/16	180	
4.8	16	15	6.73E-03	40/20	240	
6	**10**	**15**	**6.46E-03**	**40/16**	**150**	

6	12	15	5.48E-03	40/16	180	

3.5 Stage II – results

The aim of the second stage of analysis was to study the influence of the geometric configuration in the micropile group on its behaviour, and to find the configuration in which the micropile forces are minimised. Maximum shear forces and moments were also monitored, and for all of the calculated combinations, the values did not exceed the critical ones.

Sample geometric configurations of the studied micropile networks are shown in Figure 5. Results for all of the calculated combinations are presented in Table 2. The combination name contains information about the modified parameters of the pile group: the numbers after *"z1"* and *"z2"* are inclination angles for both pile groups; after *"xy"* the value that was used as modification for horizontal plane direction angle is given; and after *"dist"* the distance from the pile cap edge for *pilegroup2 is* given (for *pilegroup1,* the distance was always 0.5 m).

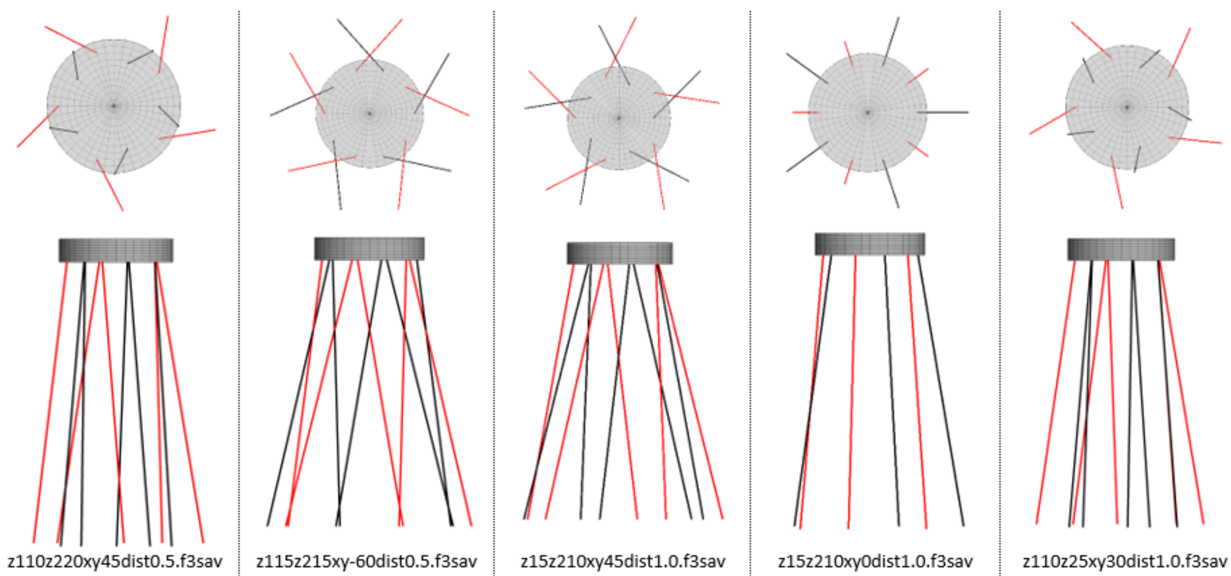


Figure 5. Sample geometrical configuration of analyzed micropile networks

Table 2. Results of stage two analysis – micropile networks

Variant name	Max disp. [mm]	Max Axial Force [kN]
z115z215xy0dist0.5.f3sav	6.54	-351.9
z110z220xy0dist0.5.f3sav	5.96	-374.2
z18z28xy0dist1.0.f3sav	6.62	-374.3
z15z215xy0dist0.5.f3sav	5.79	-374.7
z15z210xy30dist0.5.f3sav	5.56	-375.3
z110z25xy0dist0.5.f3sav	5.72	-377.3
z110z210xy-45dist0.5.f3sav	6.62	-377.8
z110z210xy0dist0.5.f3sav	**6.63**	**-378**
z110z220xy30dist0.5.f3sav	5.84	-380.2
z115z25xy0dist0.5.f3sav	5.78	-380.5
z110z210xy-60dist0.5.f3sav	6.71	-380.5
z15z210xy0dist1.0.f3sav	6.66	-381.4
z15z210xy45dist0.5.f3sav	5.63	-381.7
z15z25xy0dist1.0.f3sav	6.64	-382.1
z110z220xy45dist0.5.f3sav	5.88	-382.9
z15z215xy30dist0.5.f3sav	5.6	-384.3
z115z215xy-45dist0.5.f3sav	6.89	-385.3

Variant name	Max disp. [mm]	Max Axial Force [kN]
z110z25xy0dist1.0.f3sav	6.6	-389.1
z115z215xy-60dist0.5.f3sav	6.77	-389.8
z110z25xy45dist0.5.f3sav	5.62	-390
z110z210xy0dist1.0.f3sav	7.94	-391.5
z115z25xy30dist0.5.f3sav	5.6	-392.2
z110z25xy30dist1.0.f3sav	6.54	-393
z110z25xy30dist0.5.f3sav	5.64	-394.8
z18z28xy30dist1.0.f3sav	6.55	-394.9
z115z25xy45dist0.5.f3sav	5.67	-395.5
z115z215xy0dist1.0.f3sav	8.28	-397.8
z110z210xy30dist1.0.f3sav	6.72	-397.9
z15z210xy0dist0.5.f3sav	5.84	-399.6
z18z28xy45dist1.0.f3sav	6.68	-400.2
z15z25xy30dist1.0.f3sav	6.48	-400.3
z15z215xy45dist0.5.f3sav	5.67	-403.6
z110z25xy45dist1.0.f3sav	6.57	-404.2
z15z25xy45dist1.0.f3sav	6.56	-404.4

Variant name	Max disp. [mm]	Max Axial Force [kN]
z110z210xy-45dist1.0.f3sav	7.8	-405.4
z115z25xy0dist1.0.f3sav	7.07	-407
z15z210xy30dist1.0.f3sav	6.59	-407.8
z110z210xy-60dist1.0.f3sav	7.82	-410.6
z15z215xy0dist1.0.f3sav	7.13	-411.6
z15z210xy45dist1.0.f3sav	6.67	-412.7
z110z210xy45dist1.0.f3sav	6.72	-413.8
z115z215xy-60dist1.0.f3sav	8	-414.6
z110z220xy0dist1.0.f3sav	8.65	-417.2
z115z25xy30dist1.0.f3sav	6.77	-419.2
z115z215xy30dist1.0.f3sav	7.52	-419.7
z115z215xy-45dist1.0.f3sav	8.08	-420.2
z15z215xy30dist1.0.f3sav	6.81	-425
z110z220xy30dist1.0.f3sav	7.26	-425.1
z15z215xy45dist1.0.f3sav	6.95	-433.3
z115z25xy45dist1.0.f3sav	6.8	-441
z115z215xy45dist1.0.f3sav	7.01	-446.3
z110z220xy45dist1.0.f3sav	7.19	-450.9

The parametric study clearly showed, as could be expected in such simplified model, the following general tendencies:

- with the increasing spacing of the micropiles (smaller distance of the pilegroup from the edge of the pile cap), the axial force in the element decreases;
- as a consequence of the above, as the micropile spacing increases, the displacements decrease;
- the more “cramped” the network and interlocking arrangement of the micropiles the more limited settlements are observed;
- the more regular network in the sense of no crossing of the micropiles, the bigger the "mean” inclination of the micropile, the loading of the micropile is smaller.

Consequently, the analysis showed that the optimized solution would be the simple group, not network, of micropiles with a regular arrangement inclined 15° with no interlocking (fig. 6).

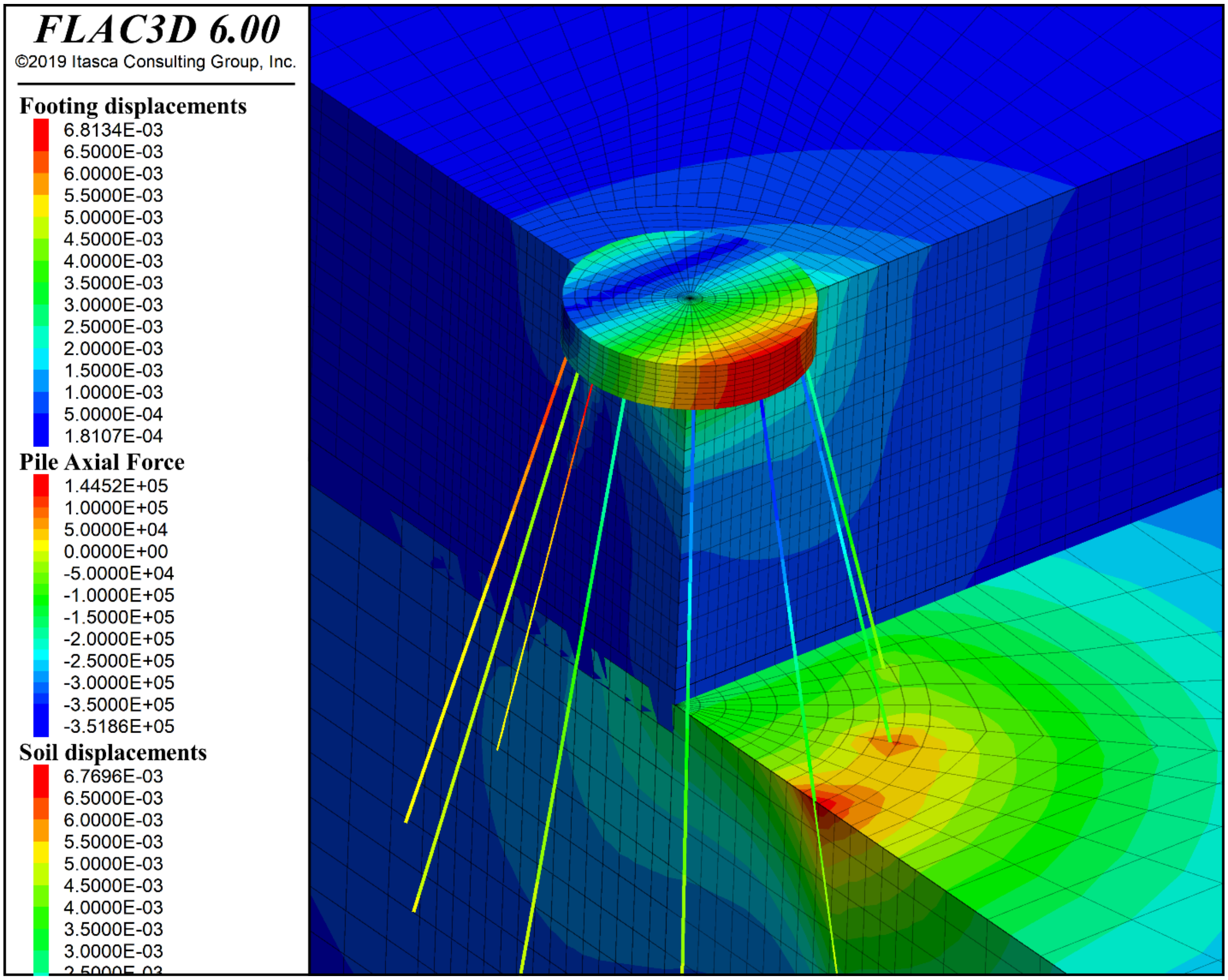


Figure 6. The micropile network variant with the minimal forces and map of the displacements

3.6 Summary

The parametric numerical analysis with automated scripts allowed the study of the influence of geometric variables on groups of micropiles in a considerable number of models, simultaneously and very efficiently. All the geometric parameters believed to be responsible for the behavior of the micropile foundation were studied. Taking into account the direct way of mapping the elements of the foundation, without any additional measures reflecting the effect of soil reinforcement between micropiles, the results of the parametric analysis are in line with expectations. The values of the displacements are reasonable and similar to those observed in practice. The axial forces in the simple micropile groups are also considered reasonable. However, in more complex arrangements this value seems to be questionable. Also, in general the positive effect of the micropile foundation is visible in the calculation results.

Nevertheless, it is clearly visible that accurate simulation of micropile networks in numerical modelling requires application of additional, non-standard procedures representing the soil confinement or lateral pressure mobilization, as reported in the literature. This should be the object of further studies, based on the algorithm and tool presented in the paper but with more sophisticated definition of the structural elements and soil behavior in the affected zone in the numerical model.

4 CONCLUSION

Nowadays the process of designing means not only the simple sizing of the structure, but also analysis of the sensitivity and study of the various options in order to get an optimized solution. The micropile foundation lends itself to this kind of optimisation, especially considering the difficulties in the description and lack of calculation tools for their complex behavior. Numerical modelling software is proven to be the most suitable solution for this kind of analysis. When equipped with sets of scripts for model generation and presentation of results it allows all the aspects of the demanding design process of the complex structures to be fulfilled.

As showed in the paper, the modular approach to the design of micropile groups with FDM numerical modelling, powered and controlled with Python scripts library, enables not only the production of trustworthy results but, which is even more important, allows extensive parametric analysis to be performed, with reduced time for modelling, and finally reaching the optimised solution. It proves to be a powerful tool, and should be a great help to geotechnical designers in the more and more demanding construction industry.

The study performed in the paper is to be continued to reproduce the group effect in the micropile network. Thus, in further analysis, the presented approach will be extended in the numerical modelling part with more complex definition of the structural elements describing micropiles and soil behavior in the zone affected by the micropile installation.

5 REFERENCES

Bustamante M., Doix B. (1985) Une methode pour le calcul des tirants et des micropieux injectes, Bull. Liaison Lab. Ponts et Chausees, nr 140, Nov.

DGGT (2014). Recommendations on Piling (EA-Pfähle). Ernst & Sohn. Berlin 2014

FHWA (2005), Micropile Design and Construction Reference Manual, FHWA Publication NHI-05-039

Itasca Consulting Group Inc., FLAC3D, Fast Lagrangian Analysis of Continua in 3 Dimensions, Minnesota: Itasca Consulting Group Inc. 2019

J. Oke, N. Vlachopoulos, M.S. Diederichs (2014) Numerical analyses in the design of umbrella arch systems, Journal of Rock Mechanics and Geotechnical Engineering 6(6):546-564

Juran, I., Jahir Hasan, Weinstein, G. M, and Sourisseau, L. (2003), FOREVER “Synthesis of the Results of the National Project on Micropiles”, International Center for Ground Improvement, Polytechnic University

Kłosiński B. (2014), Zasady i problemy projektowania mikropali według Eurokodu 7, Geoinżynieria: drogi, mosty, tunele, 26-32, vol. 9 2014

Lizzi F. Pali Radice (Root Piles) and Reticulated Pali Radice. Micropiling. In: Unde rpinning. Eds. S. Th orburn, J.P. Hutchison. Surrey University Press. Glasgow–London 1985, pp. 84–161.

Ostermayer H. (1996). Verpreßanker. Grundbau-Taschenbuch, Teil 2. Ernst & Sohn, Berlin.