MICROPILE FOUNDATION OF LARGE BRIDGE STRUCTURE ON WEAK GROUND

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ABSTRACT

The issue of bridge foundations seems to be fairly well fathomed today. In the era in which various piling techniques are available, the vast majority of bridges is placed on foundation piles. There are also many studies and publications discussing issues related to the design of piles and pile foundations.

The article discusses issues concerning modern design and construction of micropile foundations for large bridges on weak ground and provides an example of the possibilities and effectiveness of micropile technology.

1. A BRIEF HISTORY OF MICROPILES

The use of micropiles for foundation support goes back to the middle of the last century. In the early 1950s, Dr. Fernando Lizzi introduced a new way of thinking about foundations. Observing nature, he developed the idea of "root piles" (pali radice), small diameter piles which, in a correct configuration of length, inclination and spacing, form, a structure similar to a tree root system, capable of transmitting vertical and transverse forces. This elegant idea allowed the implementation of light, sophisticatedly designed foundations resulting in wide range of capacity. Due to its ability to be constructed in difficult terrain, variable ground conditions and limited space, micropile technology provides a versatile and adaptable method for the construction of special foundations.

The self-drilling TITAN system is fully compliant with BS EN 14199 "Execution of special geotechnical works", both in terms of method of micropile construction (drilling with simultaneous injection, using a stay-in-place duct as reinforcement), and material requirements (steel grade) and requisite anti-corrosion protection. The TITAN system allows a rapid pace of work, facilitates settlement prediction (based on set of nomograms), and provides high efficiency of micropile systems in load/settlement relation.

2. GENERAL CHARACTERISTICS OF THE VIADUCT

Issues presented in this article pertain to a road viaduct foundation, object WS-09, constructed along S3 expressway in the Swinoujscie – Lubawka section. The project was carried out by the General Directorate for National Roads and Motorways, the division in Zielona Gora in June 2008.

Object WS-09 is located at 9 756 to 10 160, in the section between nodes "Międzyrzec South" and "Sulechów", section 1, km 0 +000 to 17 +100 (Figure 1).

In geological terms, the viaduct foundations are situated in extensive Paklica River valley, within the lowest floodplain area, which is swamp Foundation area is a swampy, muddy and has numerous wetlands (marshes). Along the section between km 8 +500 to 11 +200, the area is protected by the so-called "protected landscape" 13 (Paklica and Ołobok Gully). Difficult access and boundaries of the protected landscape area prevented agricultural activities on the land. Before the viaduct construction, the area remained undeveloped, and overgrown with marginal lake vegetation.

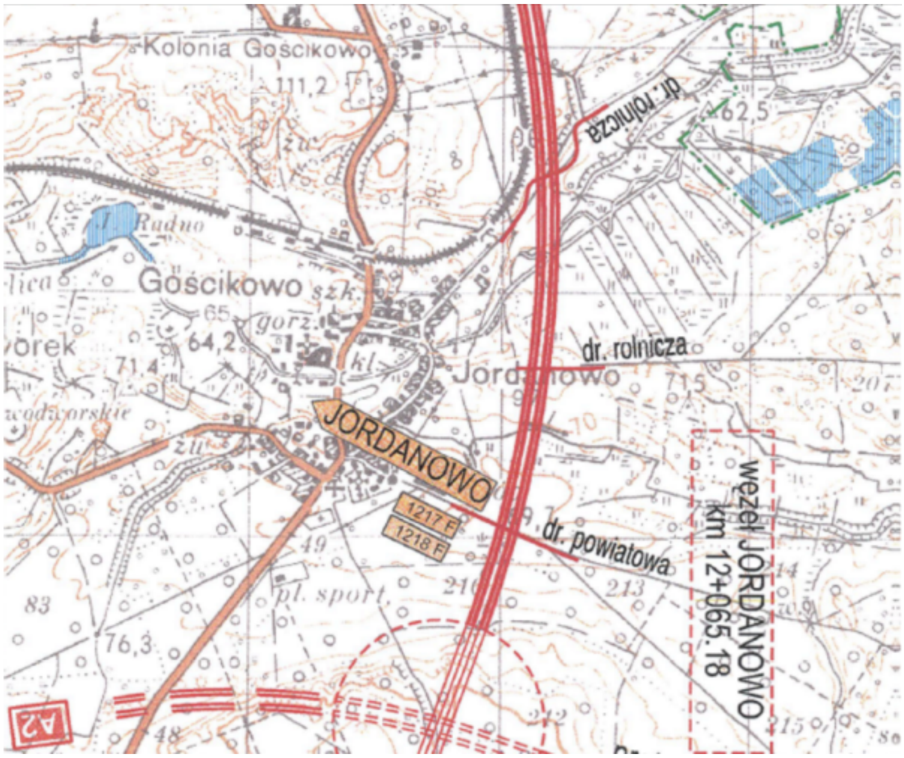

Figure 1. Situation map of the course of S3 expressway in the discussed section

The WS-09 road viaduct is a dual carriageway object, with length of 404m. Each viaduct structure consists of eight interior spans each at length of 42m, and two end spans each at a length of 34m. Each span is composed of post-tensioned, pre-stressed reinforced concrete. The maximum height of the structure is approximately 10m.

Due to both the extremely complex soil/water conditions and the conditions associated with the protected landscape, the design of the foundation was inherently problematic. Thus, all of the construction of the foundations and the superstructure, were supposed to ensure minimum interference with the protected landscape area.

3. GEOTECHNICAL AND HYDROGEOLOGICAL CONDITIONS

Engineering and geological conditions were established based on the geological engineering documentation prepared by "GEOPROJEKT - Zielona Gora" in August 2004.

Due to its origin, the entire area is characterized as difficult with variable geological conditions. The subsurface profile was determined by performing test borings at the locations of the abutments and pier foundations. The maximum expected foundation depth was about 20m below the ground level., where it was found that within that depth there is a system of alternating layers with varying thickness of organic and cohesive and non-cohesive soils.

A general description of the various layers determined at these locations is provided below.

A - glacial clays formed as silty clays, sandy clays, firm sandy clays or sandy clays with pebbles, in the structure base, soils from this group occur generally in hard-plastic state IL = 0.20, less frequently semi-firm;

values of set geotechnical parameters: $\varphi = 13\text{-}19o$, $c = 35\text{-}70$ kPa

B – marginal lake formations, formed as dust and silty calys; these occur generally in hard-plastic state IL = 0.16 or plastic $I_L = 0.33$;

values of set geotechnical parameters: $\varphi = 8\text{-}13°$, $c=35$ kPa

B3 - glacial formations, formed as loamy sands, sandy clays, these formations occur in hard-plastic state I_L=0,12-0,20;

values of set geotechnical parameters: $\varphi = 10\text{-}12°$, $c=30\text{-}37$ kPa

C – glacial formations, developed in the form of clay, silty, sandy clays, clay sands with gravel; they occur in hard-plastic I_L=0,12 to plastic I_L=0,50 states;

values of set geotechnical parameters: φ =5-13°, c=9-30 kPa

C1 – marginal lake dusts, often with additions of humus; occur generally in plastic and soft-plastic states I_L=0,40-0,58 (layer with humus admixture), rarely in hard-plastic (pure dust) I_L=0,22;

values of set geotechnical parameters: φ =3-28°, c=5-20 kPa

D – limnic clays, formed as clays or silty clays; they occur in hard-plastic state I_L=0,04-0,11;

values of set geotechnical parameters: φ =12°, c=50-65 kPa

E - organic soils, formed as gyttjas or lake chalk; they occur in soft-plastic state I_L=0,64;

geotechnical parameters have not been established

F - organic soils, formed as peat, clayey silts, sandy silts, these occur in soft-plastic state I_L=0,66;

values of set geotechnical parameters: φ =2°, c=5 kPa

I - water-glacial sands, formed as silty sands, fine sands, medium-grain sands, coarse sands with humus, coarse sands and gravel, gravel sand and gravel; they generally occur in medium-compacted state I_D=0,46-0,52 or compacted I_D=0,71-0,73, sometimes loose I_D=0,30-0,33;

In hydrogeological terms, the situation is also complicated by levels of water tables, bth free and confined. Furthermore, there are suspended waters, enclosed in lenticels. The first free aquifer level can be found at a depth of 0,4m below the ground surface in the northern part of the structure, and has a direct hydraulic relationship with the river flowing through the area. Other confined aquifers were determined between depths of 3,5m and 5,0m and between 12,0 and 14,0m. In the northern part of the area, the presence of suspended was also confirmed at a depth of about 8,0m. The confined water table was stabilized at relatively constant level at a depth between about 1,0m and 1,5m. Example soil profiles for one of the least preferred locations in the area are shown in Figure 2.

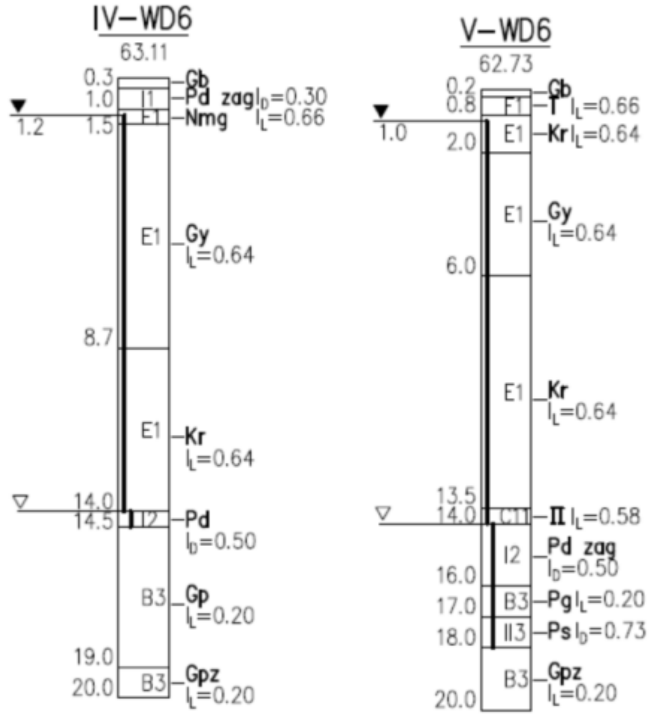

Figure 2 Geotechnical profiles of holes in the area of support D

4. DESIGNING MICROPILE FOUNDATIONS - ASSUMPTIONS, COMPUTATIONAL APPROACH

The design of micropile foundations in such complex conditions required an appropriate approach, which considered various load combinations, geometric arrangement of the superstructure, geometric arrangement of the micropile foundations and the subsurface profile and soil parameters. On this basis the required load bearing capacities of the micropiles were established. For the analysis, it was assumed that TITAN 103/78 and TITAN 103/51 micropiles would be used. Due to the nature of structural work, the footings may be subjected to variable loads. The calculations to determine the required resistance by the micropiles were carried out for the load variations listed in Table 1. The design load bearing capacities of the micropiles are summarized in Table 2.

Table 1. Considered characteristic load variations (from structural engineer)

Name in the paper	Variant	Fx [kN]	Fy [kN]	Fz [kN]	Mx [kNm]	My [kNm]
W0	Dead weight	0	0	5468.96	0	0
W1	Rz_min	-1173	258	11300	-3113.7	-16011.5
W2	Rz_max	1639	32	15838	-52.8	22372.35
W3	Ry_min	1583	942	11820	-14034.3	21607.95
W4	Ry_max	1030	-633	15364	10470.45	14059.5
W5	Rx_min	1759	342	12456	-7728.3	24010.35
W6	Rx_max	-1288	50	14459	3838.5	-17581.2

Fx, Fy, Fz – forces acting on the foundation in the direction of X, Y, Z axes; Mx, My – bending moments acting in the directions of X, Y axes

Table 2. The design load-bearing capacity of micropiles

The design load-bearing capacity of micropiles [kN]											
Support	A	B	C	D	E	F	G	H	I	J	K
East roadway	1000	800	800	800	800	1400	1000	1000	1000	1000	1000
West roadway	1000	800	800	800	800	1400	1000	1000	1000	1000	1000

Despite the use of fairly conservative design assumptions, it was decided to perform advanced spatial numerical modelling. The modelling was aimed to "x-ray" the micropile foundations and provide information not available in traditional design. In particular, the modelling focused on the evaluation of micropiles fixing, the risk of buckling and the definition of the degree of expected movements of the entire foundations. Numerical 3D modelling was therefore treated as a test instrument, at the same time providing a validation of the analytical calculations.

The numerical calculations enabled the assessment of the impact of discussed load patterns on the displacement and effort of the pile and footing system. All calculations for the purposes of this study were performed using the FLAC 3D Finite Difference

Method program. In the calculations, a cubic cube at dimensions of 50x50x50 was separated from the ground, and was composed of eight layers of soil. This area was recalculated in order to set the primary stress condition, and then displacements resulting from the original model of the stress state were reset. The next step was to model a foundation slab at dimensions of 12.5 to 5.5 m , and piles in the form of structural elements. These elements were connected to a concrete slab (lower section of pillar foundation) with rigid couplings both in terms of rotation and displacement. Connections of the structural elements with the soil were modelled as elastic plastic fasteners acting in regular directions and tangentially to the pile axis. The model was then rerun and displacements and loads were recalculated assuming its own load.

Properties of the piles and the parameters describing their interaction with the subsoil were precisely calibrated on the basis of the documented materials (load test results for micropiles of the same type in a lithologically identical substrate) obtained from the resources of TITAN Poland. In the calculations, displacement boundary conditions were assumed. Al directions on the lower plane were fixed and directions along the axis perpendicular to the respective lateral planes were fixed. This way the boundary conditions are best matched with the conditions of interaction between pile foundations and the surrounding soil.

An axonometric projection of the numerical model is shown in Figure 3.1 Projections of the numerical model in the x-axis and y-axis are shown in Figure 3.2 and 3.3 respectively. These figures show the ground conditions and the geometry of the installed micropiles.

The results of the calculations in graphical form, showing forces and moments in the piles, displacements and deformations near the footing and non-dilatational strain are shown in Figures 4.1 to 4.4.

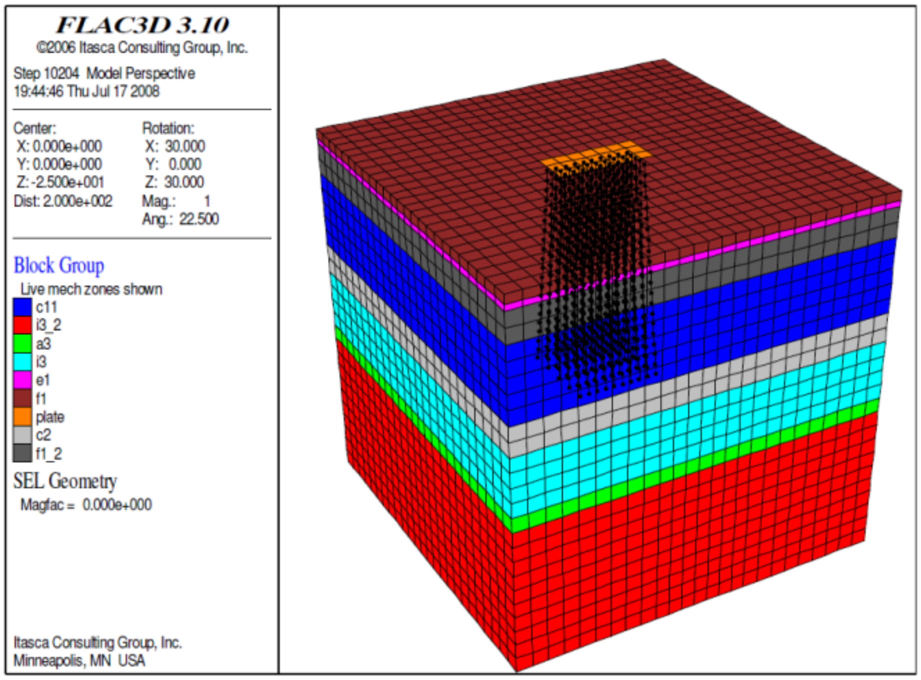

Figure 3.1 Axonometric projection of the numerical model

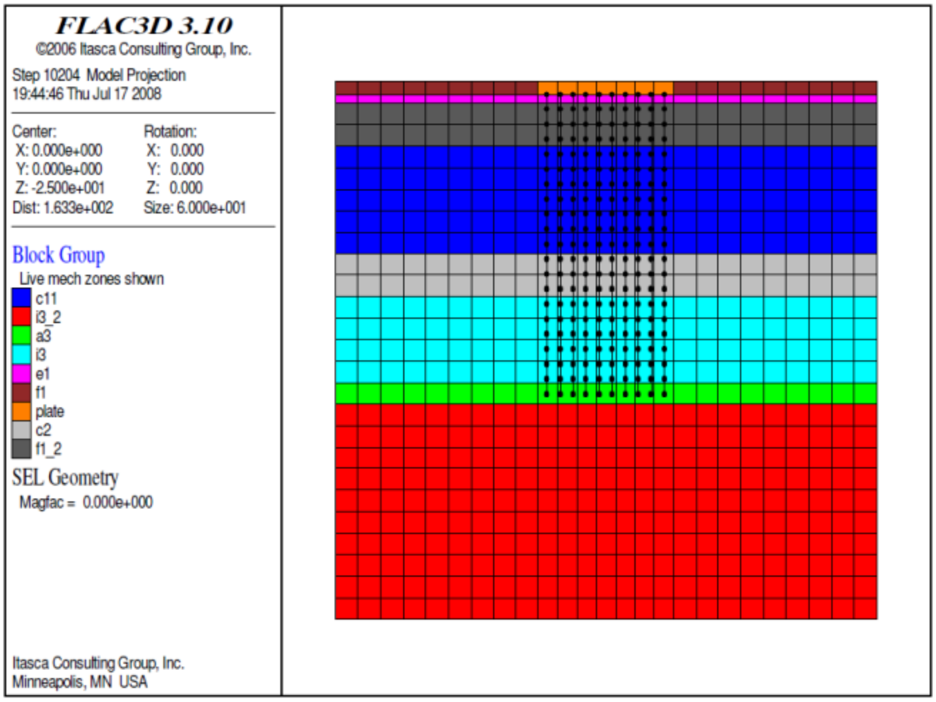

Figure 3.2 Projection of the numerical model in x-axis

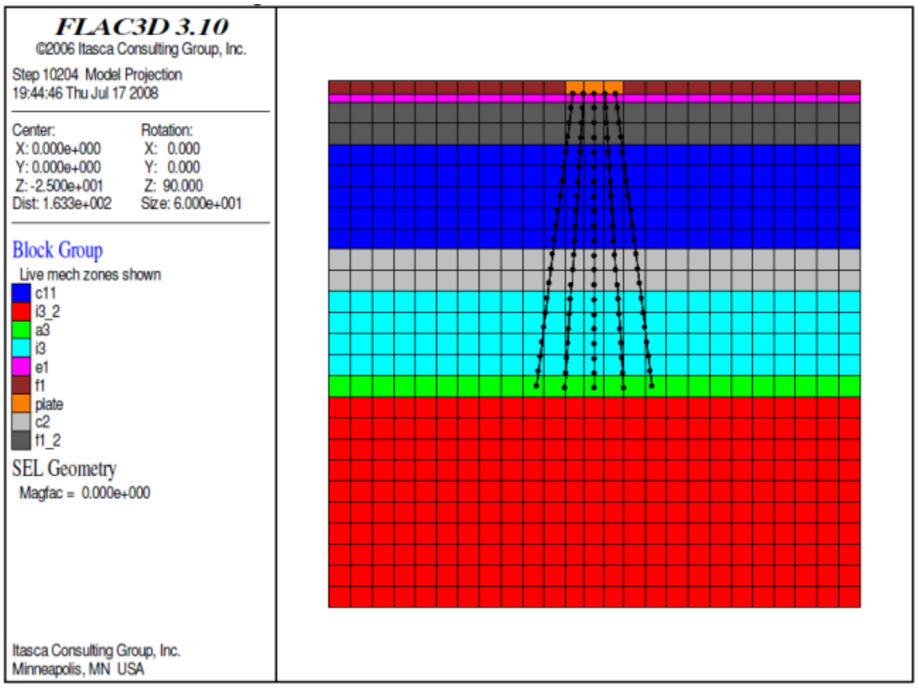

Figure 3.3 Projection of the numerical model in y-axis

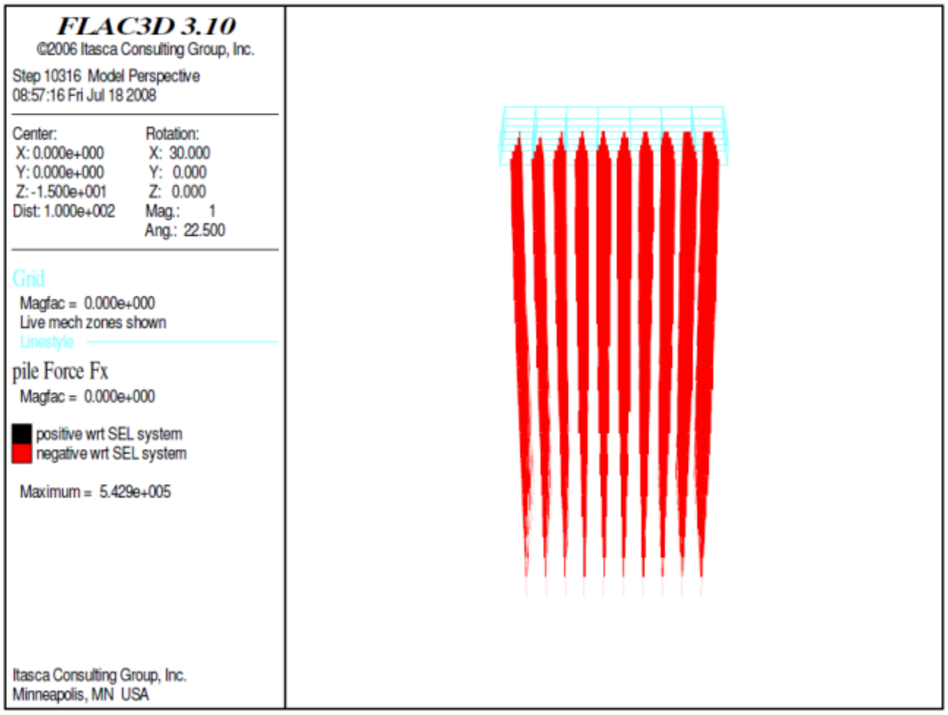

Figure 4.1 Diagram of vertical forces in piles

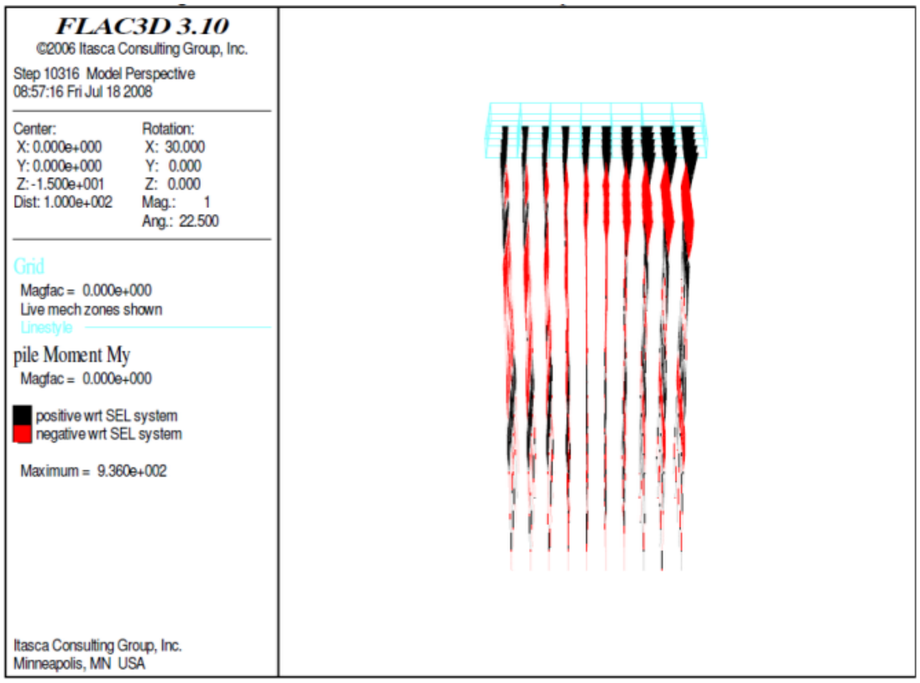

Figure 4.2 Diagram of bending moments in y axis in piles

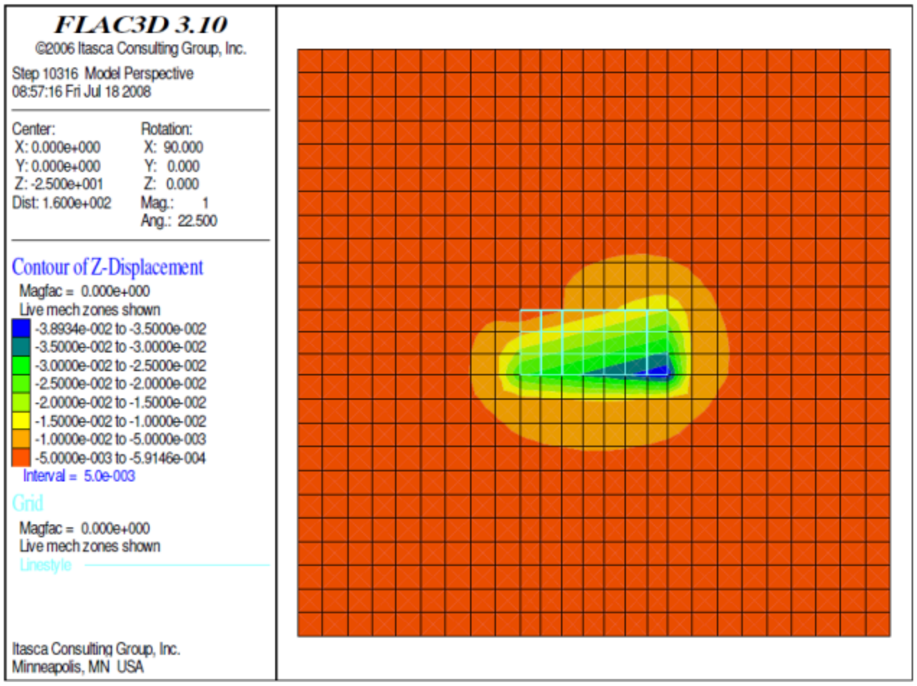

Figure 4.3 Map of vertical displacements, top view

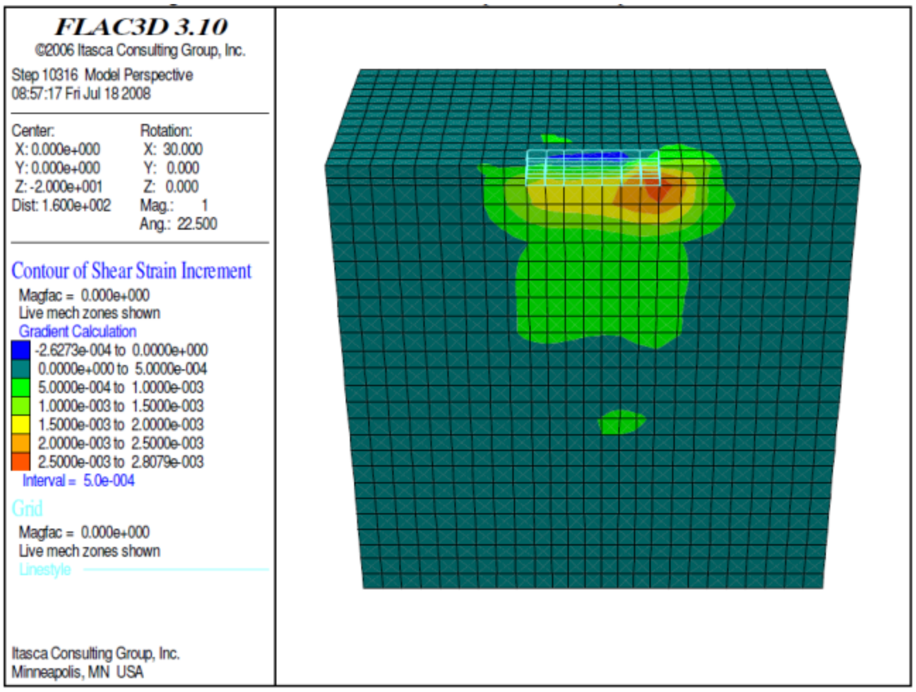

Figure 4.4 Map of non-dilatational strain in a cross-section of the longer axis of symmetry in the footing

Results from the calculations

Based on the results of the calculations, the following conclusions regarding the stability of footing can be presented for all variants of the calculation:

- The range of the maximum axial forces in the piles are (depending on the variant) between 404.1 kN (14.8% of micropile's load capacity) and 580.8 kN (21.3% load capacity);
- For all variants, the forces acting in the y- and z- directions are smaller than 1 kN and do not affect the load-bearing capacity of piles significantly;
- For all variants, the bending moments in the piles in the y- and z- directions assume values of several kNm (torsional moments in the piles are practically equal to zero) and do not affect the load-bearing capacity of piles significantly;
- The maximum horizontal displacements in the x-direction range from 6.49 mm to 14.8 mm, while the maximum horizontal displacement in the y-direction direction range from 1.51 mm to 6.71 mm; the displacement values are within the acceptable range for the stability of the footing, acc. to design specification;
- The maximum vertical displacement range from 2.34 cm to 4.18 cm; the displacement values are within the acceptable range for the stability of the footing, acc. to design specification;

- Within the subsurface, the maximum non-dilatational strains range from 1,68 mm/m to 3,41 mm/m and the volumetric strains range from 0,85 mm/m to 1,58 mm/m; the deformations are within acceptable range for the stability of the footing, acc. to design specification;

The micropile foundation provides full footing stability for various load combination. In all calculation variants (except for the zero option, W0), there is an irregular distribution of vertical displacements caused by a complex load. Adoption of a preferred system of fanned micropiles significantly reduces irregular vertical and horizontal displacements.

In fact, the displacement of the footing may be even smaller because the modelling does not take into account partial petrification of the ground caused by the installation of micropiles. These values can thus be considered as maximum, which will occur under the worst-case-scenario loadings. The presence of small bending moments in the piles is due to several reasons. The main reason for the small bending moments is the favourable, fan-shaped micropile system (resembling the trestle piles) combined with a foundation footing. This arrangement of reinforcement leads to the formation of a monolithic structure of soil reinforced with micropiles, significantly reducing the occurrence of bending moments. Another reason is the same type of reinforcement, as these are micropiles of small diameter, and low contact stiffness resulting from the interaction between the micropile and the ground with poor strength and strain properties.

It can be concluded that, for the any load case analysed, the boundary load bearing capacity was not exceeded with respect to pile foundations, and both horizontal and vertical displacement values are within the acceptable range for the stability of the footing, acc. to design specification.

5. SOLUTION DESIGN

The results of spatial numerical modelling confirmed the possibility of making the micropile foundation. Analyzing the results of modelling and analytical calculations, based on the capacities of individual micropiles, a design solution was decided for individual supports. It was agreed that each support will receive a foundation system based on 50 micropiles, arranged in five rows of 10. For the northern bridgehead, a system was designed, consisting of eight rows of micropiles with 10 pieces each, while in the south, the foundation was based on a six-row system.

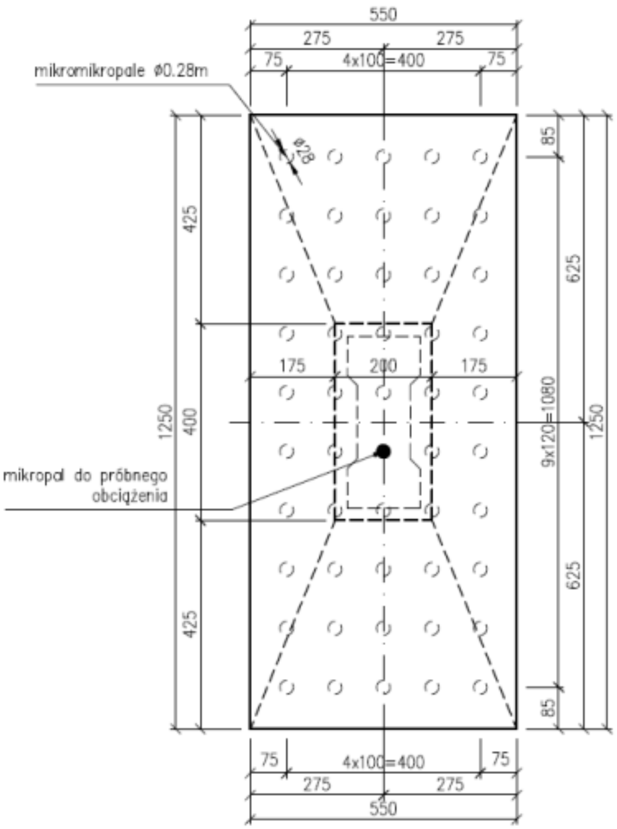

Figure 5 Distribution of micropiles in the support footing

Micropiles lengths were selected according to the geotechnical profile, taking into account the load-bearing capacity conditions for each of the supports. The correct type of reinforcement micropiles was established observing the load-bearing capacity of a single item under maximum load. Basically, the solution is based on TITAN 103/78 micropiles, with the exception of support F, for which TITAN 103/51 micropiles were used. The nominal diameter for drilling TITAN 103 micropiles is 280mm. Due to the extremely poor strain characteristics of formations near supports B, C, D and E, it was decided to use, in their foundations, micropiles made with Mono-Jet TITAN. This is a technological modification in which a drill bit system is applied, equipped with nozzles at a diameter of 3.5 mm. This allows increase in the initial and final injection pressures to about 200 bar. The other elements of TITAN does not change. The procedure is also retained with respect to the appropriate technology. Increasing pressure allows micropiles with a larger diameter, helping reach the designed capacity even in extreme conditions, while maintaining the benefits of the self-drilling system.

Final shape of micropile foundation is shown in Table 3.

Table 3. Design solution of micropile foundation for one carriageway

Support	A	B	C	D	E	F	G	H	I	J	K
Micropile type	TITAN 103/78	TITAN 103/78	TITAN 103/78	TITAN 103/78	TITAN 103/78	TITAN 103/51	TITAN 103/78	TITAN 103/78	TITAN 103/78	TITAN 103/78	TITAN 103/78
Micropile length [m]	15	18	24	24	24	15	15	15	21	21	21
Nominal diameter [m]	0,28	0,60	0,60	0,60	0,60	0,28	0,28	0,28	0,28	0,28	0,28
Number of micropiles	80	50	50	50	50	50	50	50	50	50	60

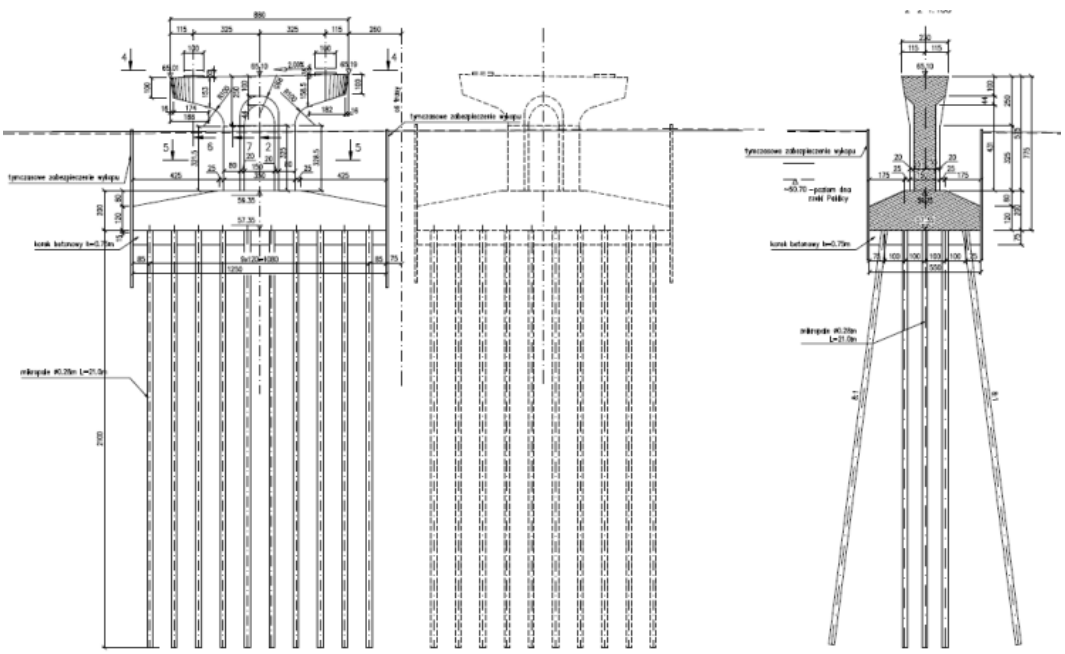

Figure 6 Cross section of the superstructure with the micropile foundation system

6. WORKMANSHIP

The construction of the micropile foundations began 8th November, 2010. A self-propelled 10 ton crawler-mounted drilling rig was used (Figure 7). In the sticky ground conditions with groundwater levels reaching almost the ground surface, the equipment of such weight and dimensions allow free operations without the need for special subsoil reinforcement, road construction or placement of working platforms. The excavation for the abutment footings were planned to be open-cast (Figure 8 and 9). Micropiles within some pillar footings were made from the ground surface, limiting the scope of the earthworks.

Fig. 7 Placement of micropiles, injection facilities in the background

The ability to relocate the injection facility, as needed, and to prepare the grout at the site highlighted the advantages of self-drilling micropiles. The cement grout mixture (for pre- and post-injection) was fed through hoses directly to the rig operated near the foundations. A mixture was fed to the drilling rig from facilities located near the main access road, which greatly facilitated the supply of cement. The need for pumping grout over considerable distances resulted in some difficulties, but it eliminated logistical problems associated with the safe delivery of grout and pumps to the correct location and on time.

Construction with the placement of foundations lasted until 18 July 2011, with the actual micropile construction lasting 196 days. At this time 23 679 meters of micropiles were installed, which translates into an average yield of 140 m/day. Given that the works took place in the winter and during sever frosts, the average production rate should be considered excellent.

Fig. 8 Micropile foundation before being poured over by concrete

Fig. 9 Footing after pouring concrete

Fig. 10 Pillars ready for span concreting

7. MONITORING AND VERIFICATION OF THE CALCULATION METHOD

To ensure proper quality control, the project included testing on the constructed micropiles. Load tests were performed for each support, on one from each group within its footing. Representative results from load tests are shown on the graphs in Figures 11 and 12, which indicate rapid stabilization of settlement and largely resilient nature of the displacement. A summary of the average micropile loading and settlement for different types of micropiles is shown in Table 4. Ongoing geodetic monitoring was provided during the construction within which settlement of each support at different constructions phases was measured. The results indicated settlements of finished pillars at an order of 1 mm to 4 mm.

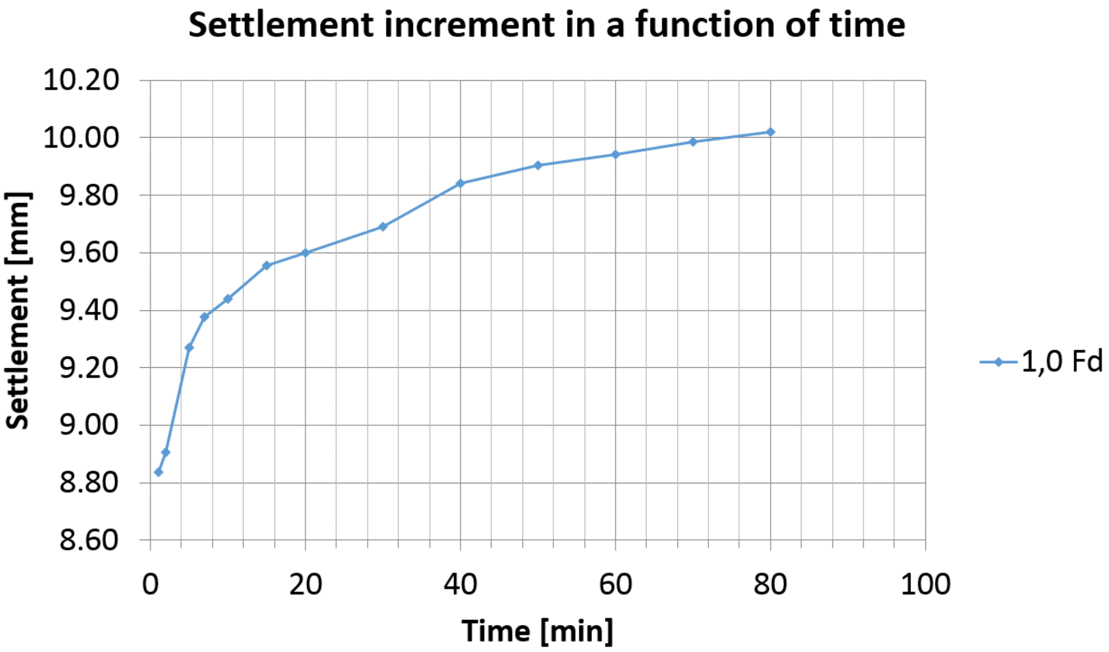

Figure 11 Graph of the load and relaxation curve

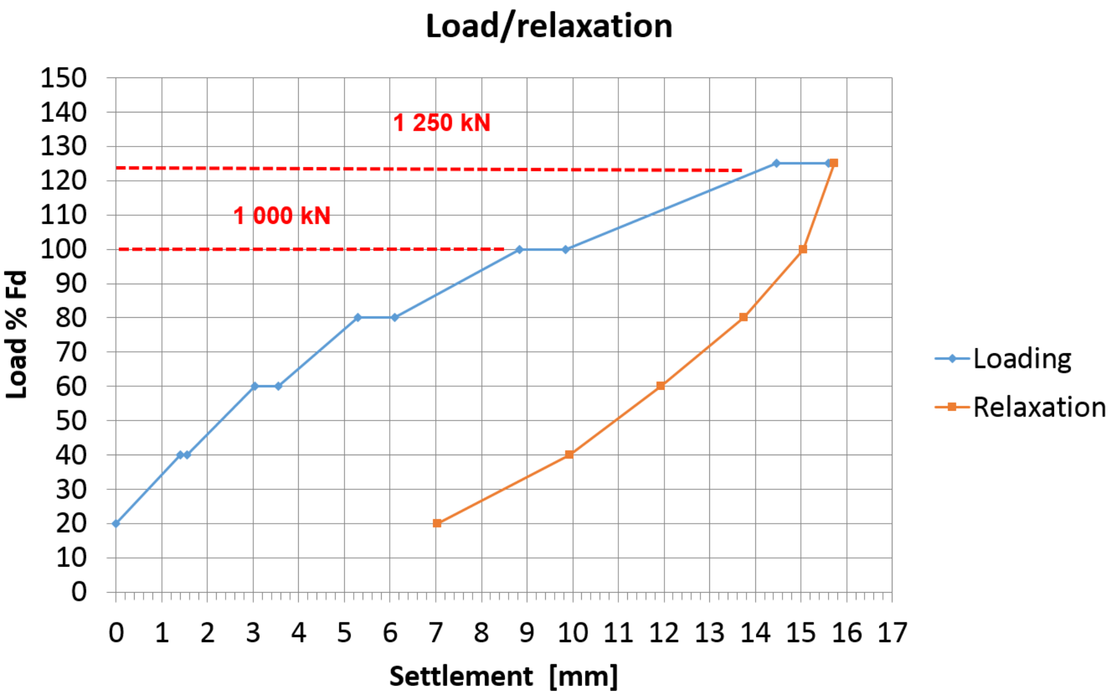

Figure 12 Stabilization of settlements at a design load of 1,000 kN

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Table 4. Comparison of average micropile settlement

Micropile type	Length [m]	Load design [kN]	Average settlement [mm]
TITAN 103/51	15	1 400	15,70
TITAN 103/78	15	1 000	10,58
TITAN 103/78	21	1 000	13,17
TITAN 103/78	24	800	15,37
TITAN 103/78	18	800	13,91

8. CONCLUSIONS

Experience gathered to date allows the formulation of some conclusions and remarks summarizing the stages of construction thus far.

1. The design solution of foundations, using micropiles, going beyond the confines of the universal engineering practice proved to be accurate and effective.
2. The micropile technology used in the project enabled the achievement of a number of technical and economic advantages: a significant simplification of logistics, cost reduction by minimizing the extent of preparatory works, earthworks, drainage, etc. in an area with difficult accessibility.
3. Excellent progress, and short duration of the foundation placement.
4. In addition to the technical-economic aspect, the technology enabled construction with minimal interference in the environment, preserving the qualities of a protected landscape area.
5. Application of advanced computational methods supports the design process, allowing optimized solutions.
6. The results of comprehensive monitoring will be used to better understand how micropile foundations work, allowing a better, subsequent calibration of numerical models.
7. An extensive network of benchmarks and systematic measurements enable the collection of valuable information about the functioning of micropile foundations as a whole, in particular about the total load-bearing capacity and settlement in a complex group of micropiles.
8. The ability to verify the results of numerical modelling in a full-scale solution helps broaden technical awareness and create a knowledge base thanks to which in many cases the construction will be free from the constraints of conventional design approach.
9. Micropile foundations, using TITAN technology are characterized by very favourable operating characteristics (small settlement, fast stabilization).
10. Technology gives the ability to place heavily loaded foundations in complex ground conditions and difficult terrain, virtually regardless of the weather conditions.
11. In such a weak substrate, a huge role was played by the technological factor - drilling with simultaneous injection, which allowed (apart from elements at a certain unit load-bearing capacity) an injection merger, petrifying the ground within the micropile system. This, in turn, allows the treatment of this type of foundations, as a deeply monolithic, geo-composite bodies, characterized by

much more favourable properties than would result from summed load capacities of individual components.

12. The idea of "root piles" is harmonized perfectly with TITAN technology, allowing the use appropriate solutions.

9. LIST OF MATERIALS USED

1. Fragments of the Implementation Project carried out by "Transprojekt" Krakow Bureau of Road and Bridge Projects Sp. z o.o. by M. Sc. Eng. Robert Słota and M.Sc. Eng. Janusz Jedrychowski, in June 2008, concerning S3 Świnoujście-Lubawka-State Border dual carriageway, section between nodes „Międzyrzecz Południe” and „Sulechów” km 0+000 – km 42+953,96,
2. Spatial modelling of working conditions for micropile foundation supports for the proposed flyover over S3 expressway, section Międzyrzecz – Sulechów, M. Cała, M. Kowalski, Kraków, July 2008