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Settlement of large pile groups on the example of bridge foundations supported on driven precast piles

Tassement des grands groupes des pieux préfabriqués comme un exemple de foundation des ponts

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ABSTRACT: This paper presents the issue of pile group settlement in reference to the currently constructed infrastructure project in Poland – Construction of the A1 Motorway. The article contains characteristics of four bridges founded on large pile groups consisting of driven precast concrete piles. Pile foundations were designed on the basis of soil investigation in situ including CPT. For one of the bridges the soil recognition was extended by performing dynamic probe test DPH and using modern geophysical surveys based on seismic waves. In order to confirm the design assumptions a very extensive pile test program was carried out that 20 % of all piles were tested including a total of 36 static load tests (SLT) and 280 dynamic load tests (PDA). The pile foundations of the analysed bridges, founded in the complex ground conditions of the Cracow-Czestochowa Jura, are subjected to enormous vertical and horizontal loads as well as bending moments. Therefore, large groups of 120 to 260 piles were designed in the foundation within one support. A wide program of research conducted on the project assumes constant monitoring of the constructed objects in terms of their displacement in time. The first measurements of settlement have already been made and will be carried out throughout the construction period and through the subsequent years of exploitation. Comparison of settlements estimated during design analysis and obtained in the monitoring is presented and discussed. Conclusions of the analysis are a very reliable source of knowledge about a large pile group behaviour.

RÉSUMÉ: On traite dans l'article le problème de tassement d'un groupe des pieux préfabriqués exécutés pour les ponts de l'autoroute A1 dans la région de la ville Częstochowa en Pologne. La charactéristique de quatre ponts fondés sur un groupe des pieux préfabriqués on béton armé est presenté. Le projet des pieux est base sur la reconnaissance du sous-sol à l'aide de pénetromètre statique CPT. Pour un objet de pont, la reconnaissance du sous-sol a été élargie par les sondages exécutés avec le pénetromètre dynamique et les mesures géophysiques basées sur les ondes seismiques. Pour vérifier les hypotheses de calcul, il a été realisé un large programme d'études des pieux testés. On a examine 20% de tout les pieux dont 36 études statiques et 280 dynamiques. Les fondations realisées dans les conditions géotechniques compliquées de la Jura de Cracovie – Częstochowa, sont charges par les énormes forces verticals, horizontals et moments fléchissants. Pour un appui de foundation du pont, un nombre de 120 à 160 d'un groupe des pieux a été exécuté. Dans ce large programme d'étude des pieux un monitoring continu des mesures de tassement sur tout le objet de pont a été prevu, dans le temps de construction du pont et dans les années suivates après sa construction. Les resultats des tassements obtenus déja ont été compares avec ceux obtenus de calcul et ceux d'observation dans des années suivantes. Les conclusions obtenus de l’analyse des résultats seront une source véritable pour les conditions l’interaction du sous-sol et la construction du pont.

Keywords: pile group, settlement, pile foundation, driven precast piles, structure monitoring

1 INTRODUCTION

Construction of infrastructure in Poland has been experiencing a period of dynamic development for several recent years. It concerns projects carried out in the field of road and rail infrastructure as well as bridge and maritime construction. This situation due to the complexity of the projects is always a challenging job for engineers. However, it provides invaluable opportunities for development in the field of design methods and technology of construction works.

One of the currently constructed infrastructure projects in Poland is construction of the A1 motorway near Czestochowa. This strategic project in terms of country’s economic growth is carried out in the complex ground conditions of the Cracow-Czestochowa Jura. Most of the bridge structures located along the planned road section have been founded using pile foundations. Foundations of four bridges were designed and constructed as large pile groups consisting of driven precast concrete piles.

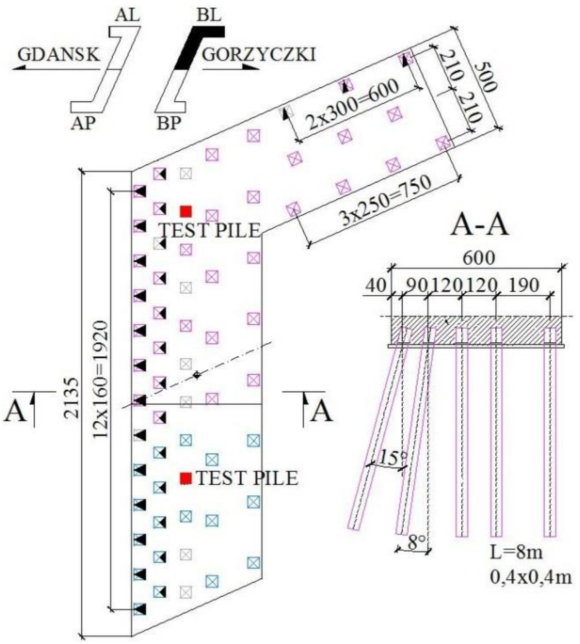
The analysed bridges are currently under construction and monitoring of their settlement is carried out up to date. Settlement results obtained on the basis of geodetic measurements will be compared with the results of the vertical displacement calculations included in the foundation project. The basic purpose of the research is the detailed analysis and comparison of existing calculation methods for the estimation of the settlement of pile in group and the analysis of actual behaviour of pile foundations.

2 CONSTRUCTION DESCRIPTION

The bridge constructions preliminary named M- 1, M-2; M-3; M-4 (Figure 1) will serve as bridges over watercourses and as a crossing for animals under the motorway.

Figure 1. Construction site of bridges M-2 ;M-3

Each of the analysed objects has a similar construction system that consists of two massive abutments founded on driven precast piles surmounted by a reinforced concrete slab. The bridges span length varies from 22 m to 41 m. All the bridges are dilatated within the separation line between the left and right carriageway of the motorway. Hence four separate foundation supports AL, AP, BL, BP can be extracted (Figure 2).



Figur 2. Pile system – M-1, BL support

The pile foundations of the analysed bridges, founded in the complex ground conditions of the Cracow-Czestochowa Jura, take on vertical and horizontal loads as well as bending moments. Transferring loads to the deeper subsoil layers is carried out by using precast, reinforced concrete driven piles with a cross-section 40 x 40 cm. There are large pile groups within each foundations numbering 252 piles and 8 to 12 m in length for M-1, 285 piles between 12 to 15 m in length for the object M-2, 344 piles 10 to 13 m long for M-3 and 520 piles from 10 to 17 m long for M-4. The maximum load per single pile is 1000 to 1400 kN. The average axial spacing between piles in the group is 1,2 m within abutment central panel and 2,5 m in the wing-walls area (Figure 3).

Figure 3. Construction site view of M-2

3 GEOTECHNICAL CONDITIONS

Pile foundations were designed on the basis of soil investigation *in situ* including CPT. There are four cone penetrometer tests carried out for each of the bridge structures within four extracted supports. For one of the bridges the soil recognition was extended by performing dynamic probe test DPH. There are layered soils with highly diverse strength parameters within subsoil (Figure 4). There are alternating cohesive layers (clays, sandy and silty clays, silts) and non-cohesive soils (sands, clayey sands). Pile toes are embedded in residual clay layer in M-1 foundation. In the case of M-2 and M-4 pile toes end in sand layers while for the M-3 piles reach sandy and silty clay layers.

4 PILE TEST PROGRAM

In order to confirm the design assumptions a very extensive pile test program was carried out that 20 % of all piles were tested including a total of 36 static pile load tests (SPLT) and 280 dynamic load tests using pile driving analysis (PDA). There were 8 static load tests carried out in the

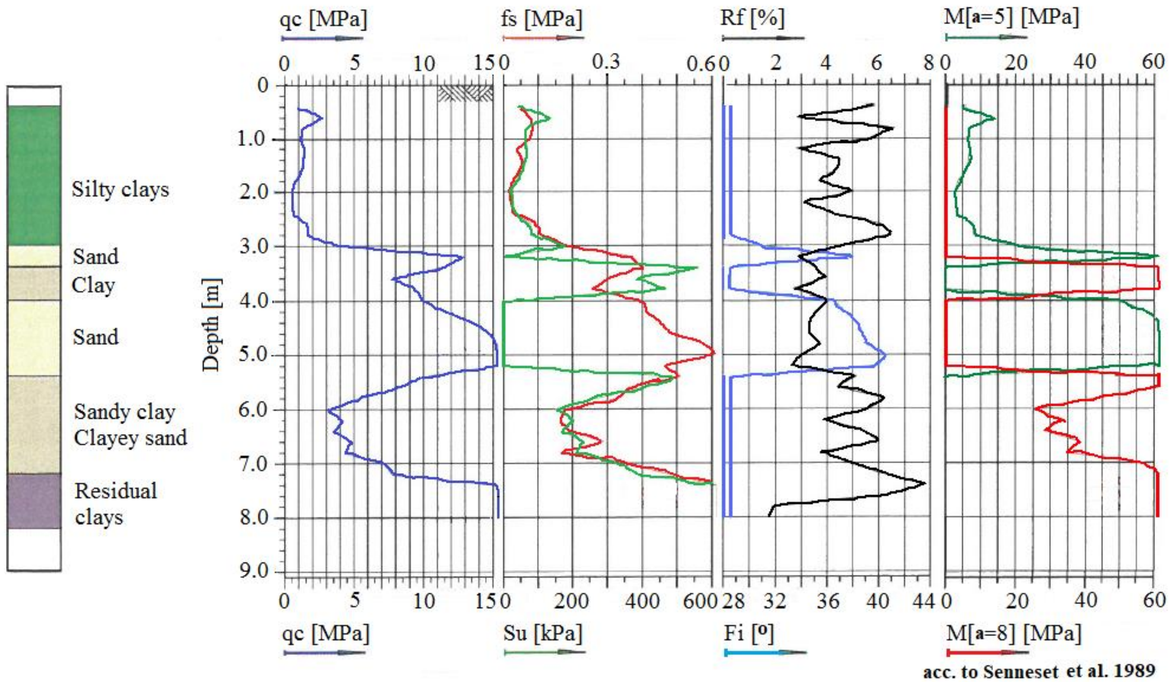


Figure 4. Geotechnical conditions – bridge M-1, support BL

case of each bridges M-1, M-2 and M-3 and 12 static load tests for M-4. The pile test phase was carried out before target piling to confirm design assupmtions. During the testing phase for M-1 some deficiencies in axial bearing capacity of piles were received within the area of BP support. Therefore it was necessary to extend soil recognition in this zone. According to the driving parameters analysis, it was expected that the layer of residual clay has a very irregular collocation. Hence it was decided to carry out geophysical surveys based on seismic method with the use of multi-channel analysis of surface waves and refractive tomography. On the basis of the analysis of the examined cross-sections in geophysical investigations, the results of pile tests and pile's driving data, the length of the piles before the target piling was changed. Piles on the BP support were lengthened whereas on the A support the solution was optimized by shortening the length of piles in some areas of the foundation. There is a map showing the subsoil profile on the B support based on the geophysical survey, shown in Figure 5.

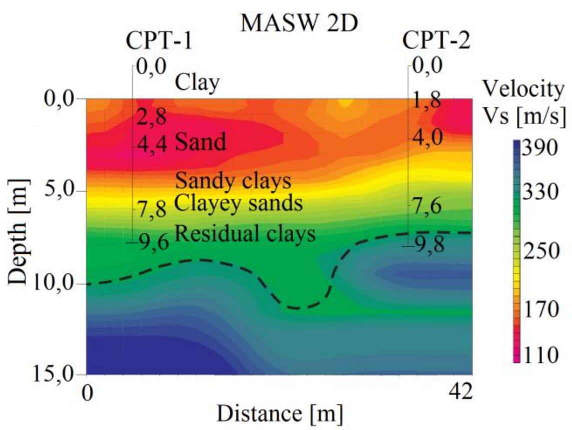


Figure 5. Subsoil profile based on geophysical survey – bridge M-1, Support B

5 PILE GROUP SETTLEMENT ANALYSIS

5.1 Methods

It is now well recognized that the behaviour of a pile group can differ significantly from that of a single pile. This is because the zone of soil which is stressed by the entire group extends to a much greater width and depth than the zone beneath the single pile. In all cases the elastic and consolidation settlements of the group are greater than those of a single pile carrying the same working load as that on each pile within the group (Tomlinson & Woodward 2008). Also the interaction between piles within the subsoil results in different settlement of each pile in a group. Settlement of the pile group cannot be equated with the settlement obtained on the basis of the load – settlement curve, plotted on the basis of the static pile load tests for a single pile.

Methods commonly adopted for the estimation of the settlement of pile groups can be divided into three main subgroups:

- The settlement ratio method, in which the average settlement *w* of a group of *n* piles may be estimated by multiplying the settlement of a single pile w_s at the average load level by a group settlement ratio *Rs*, which is an increasing factor and reflects the effects of group interaction between piles;
- The equivalent foundation method, in which an evaluation of the settlement of a pile group can be obtained assimilating the group to an equivalent raft foundation or to a single equivalent pier, in order to take advantage of the procedures for the computation of settlement of these types of foundations;
- Analytical methods based on the theoretical assumptions, in which pile-soil-pile interactions are analysed. In these approaches numerical codes such as the finite element method, the finite difference method and the boundary element method are often used.

5.2 Calculations and results

In the case of analysed bridge foundations, settlement analysis was based on the method presented in Mandolini et al., 2005. The computational approach described in this publication is an example of the settlement ratio method. The group settlement ratio *Rs* is a function of geometrical factors as the number *n*, the spacing *s* and the slenderness *L/d* of the piles. On this empirical basis the following expressions for the upper limit $R_{S,max}$ and the best estimate of R_S, as a function of the aspect ratio $R = (ns/L)^{0.5}$ introduced by Randolph & Clancy (1993), have been found:

$$R_{s,max} = \frac{w_{\max}}{w_s} = \frac{0{,}5}{\mathrm{R}} \cdot \left(1 + \frac{1}{3 \cdot R}\right) \cdot n \tag{1}$$

$$R_s = \frac{\mathrm{w}}{w_s} = 0{,}29 \cdot n \cdot R^{-1{,}35} \tag{2}$$

Equations (1) and (2) allow a preliminary evaluation of the maximum expected and the most probable values of the settlement. Table 1 presents the results of pile group settlement calculations in accordance with the guidelines of Mandolini et al., 2005. Settlement of the central panel of foundations and the wing-wall area was analysed separately due to the large size of the supports. The settlement of the single pile w_s is obtained by load tests on single pile under the average working load *Q/n* of the group (*Q* = total load applied to the foundation; *n* = number of piles).

5.3 Settlement monitoring

A wide program of research conducted on the construction site assumes constant monitoring of the constructed objects in terms of their displacement in time. The first measurements of settlement have already been made and will be continued throughout the construction period and through the subsequent years of exploitation.

Table 1. Results of pile group settlement calculations

PILE GROUP SETTLEMENT *w* [mm]				
Bridge	**AL**	**AP**	**BL**	**BP**
M-1 (R_s)	6,8	9,8	10,2	6,3
M-1 ($R_{s,max}$)	18,9	18,9	28,7	24,7
M-2 (R_s)	12,8	12,8	13,9	17,7
M-2 ($R_{s,max}$)	35,1	35,1	37,6	47,9
M-3 (R_s)	8,2	8,2	16,7	13,3
M-3 ($R_{s,max}$)	23,2	20,9	61,1	37,8
M-4 (R_s)	13,1	14,5	11,4	11,6
M-4 ($R_{s,max}$)	37,6	42,1	31,2	32,7

The construction of the bridges started in 2017 and while the pile works were finished at the end of 2017. In April 2018 after concreting the massive abutments first measurements of the bridges settlement were carried out. There are eight measurement points on each bridge (Figure 6). Overall performance of the structures has regularly been monitored during the construction process up to date. The latest measurements are dated on September 2018.

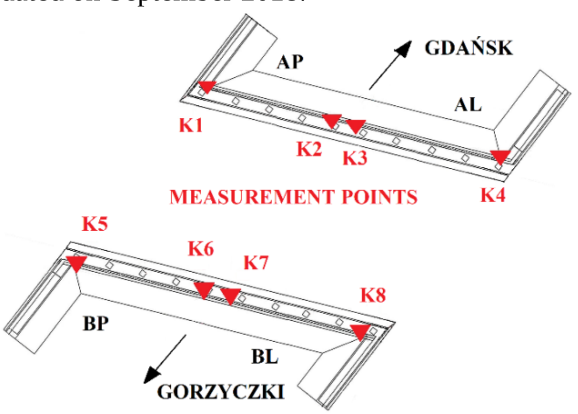


Figure 6. Measurement points location

The measurement results presented in Table 2 refer to the moment that the entire reinforced concrete structure is done for bridges M-1, M-2, M-3. At that moment, on the object M-4 prestressed concrete beams were already laid but there was still no concrete deck on the bridge.

Table 2. Settlement results measured in field tests

MEASUREMENT RESULTS *w* [mm]					
Foundation		**M-1**	**M-2**	**M-3**	**M-4**
K1	AL	4	10	16	11
K2	AL	4	13	26	13
K3	AP	-	17	30	5
K4	AP	3	17	25	4
K5	BL	3	9	27	10
K6	BL	3	9	30	11
K7	BP	-	11	30	10
K8	BP	3	13	25	7

5.4 Results comparison

The comparison of the calculation results obtained from the presented method with measured values shows that the method provides acceptable prediction of the settlement for pile groups (Figure 7). It should pointed out that the first measurement “0” was taken right after concreting the abutments and foundation slabs, which represents 40% of the total load of the foundation. It means that measured values are less than assumed for the full load. Overall performance of the foundation will be regularly monitored during the further construction process and after completion of the bridge until the moment of the settlement stabilization. It is worth noting the fact that the expected settlement of the foundations may increase after the completion of the motorway. On the basis of presented foundations M-1, M-2 and M-4, it can be concluded that the method works quite well in cases when pile toes are embedded in residual clays or dense granular soils. Then the most reliable is to use the best estimate of group settlement ratio R_s. In the case of the M-3 foundation that pile toes end in cohesive soils, it can observed some underestimation of settlement using R_s ratio. A more reliable result is obtained by multiplying settlement of a single pile by the R_{smax} coefficient.

The method is a very simple and useful approach for a wide range of pile group geometries. It is suitable for the estimation of the average settlement of pile foundations nevertheless we cannot obtain the settlement of each pile within the group. The method can also provide a useful check for more complex and complete pile groups settlement analyses, however, it should be used with caution for the analysis of pile groups with a complex geometry, different pile lengths or where the loading is highly non-uniform.

6 SUMMARY

Main source of the knowledge about the phenomena occurring within the interaction zone between piles and soil medium are observations of structures founded on piles, results of model tests and calculation analyses based on the theoretical assumptions and making use of numerical codes. Serious difficulties in the modelling of factual pile work in the subsoil restrict the use of model tests to the qualitative analysis of the phenomena investigated, only. The quantitative analysis can be carried out using field observations of existing and currently constructed structures on piles supported by analytical verification of phenomena analysed.

The settlement of the pile group depends on several phenomena occurring during transmission of loads in to the subsoil. Only some of them are already defined and elaborated theoretically. Detailed analysis of the results of measurement and calculations enables accurate verification of existing calculation methods and contributes to expanding knowledge about a pile group behaviour.

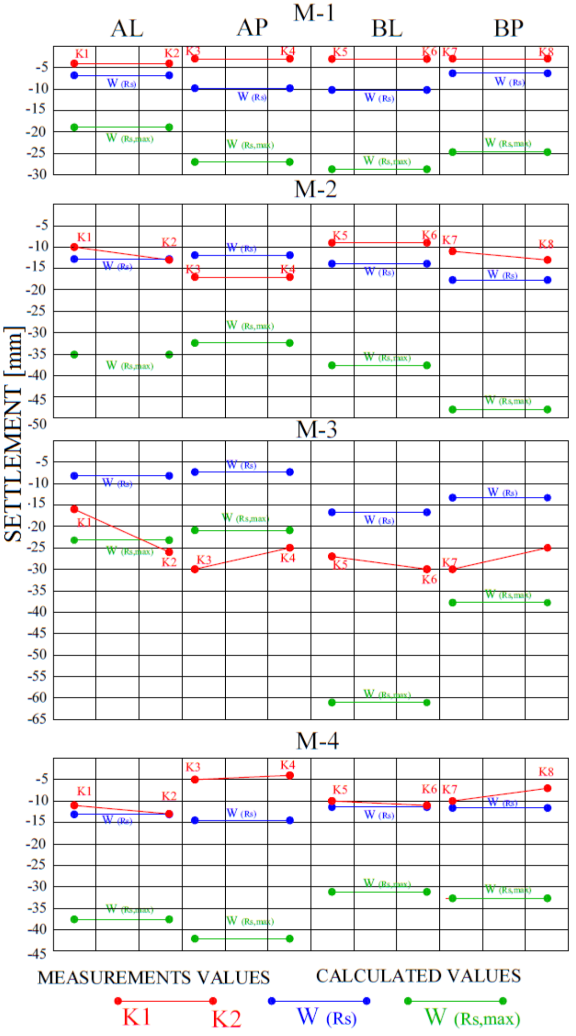


Figure 7. Results comparison

Construction of new buildings should be accompanied by long term settlement measurements. In particular, it concerns pile groups of tall buildings or bridge structures for which the most important parameter is vertical displacement under average working load. Accurate measurements should be carried out during the construction process as well as the exploitation phase.

The results of conducted research program will form the basis for future more sophisticated analyses using advanced calculation techniques such as FEM or Dyka's method (Dyka, 2001). Different soil constitutive models (hardening soil, soft soil), the groundwater flow and the impact of the applied pile works technology will be taken into account.

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