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Horizontal Displacement Control in Course of Lateral Loading of a Pile in a Slope

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Abstract. Standard procedures concerning axial and lateral capacity testing of foundation piles usually consist of a single loading cycle. Constant load steps or constant settlement increments may be applied in the test. Such a procedure significantly differs from in-situ conditions of pile loading, which can be cyclic – especially in the case of the constructions, which are subject to wind load. Several tests were performed to observe the behaviour of the driven piles subject to fast cyclic loading in horizontal direction (lateral load). The manner in which the load tests were performed made it possible to determine the displacement of the 40×40 cm pile in the least favourable loading scheme, i.e. the lateral load capacity of the pile oriented towards the embankment slope. The piles were originally designed for the foundation of noise barriers along the highway. Some of the piles were broken in course of driving and a cautious check of their behaviour under load was requested before the assembling of the entire structure. Eight load tests were carried out altogether. While selecting the piles for further load tests, the representativeness of the random sample was taken into account. The piles with diverse cross section and length were chosen, on the basis of the previous low strain tests of their integrity. The subsoil around the piles consisted of medium and coarse sands with the density index I_D>0.67. The pile heads were free. The points of support of the reference frame to which the sensors were fastened were located at the distance of 0.6 m from the side surface of the pile loaded laterally. In order to assure the independence of measurement, additional control (verifying) geodetic survey of the displacements of the piles subject to the load tests was carried out. The research conducted at Wroclaw University of Technology made it possible to collect and summarize the results of displacement measurements in course of static load testing of driven piles in a slope. Only selected case studies of cyclic loading in horizontal (lateral) pile load tests are presented in the paper.

1. Introduction

State of the art in non-destructive testing of piles was presented by Hoła and Schabowicz [1]. The suitability of acoustic testing methods for one-side only accessible elements was juxtaposed by Schabowicz [2]. In general, according to Eurocode 7, pile foundation design should be based on the results of a static load test. Standard procedures implemented in local codes of practice, concerning axial and lateral capacity testing of foundation piles, usually consist of a single loading cycle where constant load steps or constant settlement increments may be applied.

Such a procedure significantly differs from in-situ conditions of foundation pile loading, which can be cyclic – especially in the case of the constructions, which are subject to wind load. Several tests were performed to observe the behavior of the driven piles subject to fast cyclic loading in horizontal direction (lateral load). The construction of an independent reference system is very complicated when horizontal testing of a pile in a slope is considered. Some preliminary remarks were given by Muszyński & Rybak, [3]. In a static horizontal load test, the acknowledged criterion is the value of displacement. That means that the pile load capacity is understood as the force at which the pile will get displaced at the distance of 10 mm. In this case, any underestimation of the displacement leads to an overstated value of the pile's load capacity. The case becomes even more complex when the cyclic loading is considered. The increasing displacements or settlements may even change the static scheme, by forming a gap between a pile and the soil (Rybak, [4]).

Basing of the wide range of application of laterally loaded piles, the reliability of piles subjected to horizontal loads was recently widely analyzed (Puła and Różański, [5]). Also the variability of surrounding soils is being examined (Kozubal et al. [6]) and the suitability of various numerical models (Bauer et al. [7], Baca and Brząkała [8]).

Methods of displacement monitoring were examined by the authors and, on the basis of former experience, some recommendations can be given on the number of load steps necessary to achieve a steady state of soil response on cyclic load. It is noteworthy that the survey carried out by means of a geodetic method revealed greater values of horizontal displacement, which undermines the validity of the "independence" of the reference base with the dial indicators (Muszyński & Rybak, [3]). Moreover, the value of the permanent displacement after unloading was larger in the case of the measurement using the sensors. That means that the adjacent piles which formed the framework for the reference beam with sensors could have been subject to permanent displacement during the test.

2. Methods of horizontal displacement determination

Alignment method also known as constant straight line method – is the most frequent way of surveying the displacement of elongated objects. By means of that method it is possible to determine horizontal displacement in the direction that is perpendicular to a vertical reference plane. The system of reference is established by four points joined with a straight line, two at each side of the structure under survey, outside the zone of deformation (Figure 1).

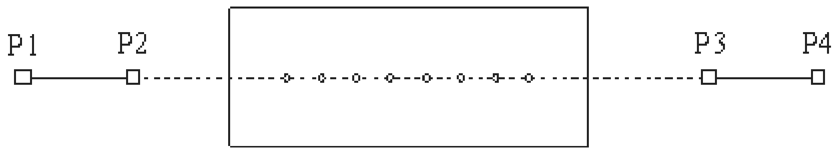

Figure 1. Alignment method scheme: □ - reference points, o - control points

Whenever possible, the location of the points is selected in such a way so that the control points are situated along the reference plane, at a short distance (up to several centimetres) and at a similar height. The instrument is placed on point P2, via forced centring, and the target – on point P3. The surveying is carried out by means of special stable theodolites with telescopes with large magnification, called alignment telescopes, or high-precision electronic tacheometers. The measurements are taken in two positions of the telescope, sometimes in several measurement series. Mutual fixity of the points of reference is controlled by analysing their horizontal displacement and by checking the horizontal angles in relation to the established additional reference points.

Depending on the method of horizontal displacement measurement at the control points, there are the following varieties of the methods formerly described by Muszyński & Rybak [3].

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Geometric-alignment method, in which the vertical reference plane is determined by the target axis of a theodolite or an alignment telescope placed in point P2 and oriented to point P3. In each of the control points a special target is positioned, which is shifted by means of a micrometric screw to fit into the target line (Figure 2). The values of horizontal displacement in the crosswise direction to the reference line are calculated by means of a comparison of the readouts from the micrometric screw that come from different survey periods. Sometimes mobile targets are used and the value of the transverse displacement is read out from an alignment telescope with an optical micrometer.

a) b) c)

Figure 2. a) theodolite Theo 010, b) and c) a slidable target with a scale and a nonius

Trigonometric-alignment method, in which a high-precision tacheometer is sighted on an immobile target (situated in the control point) and the parallactic angle is measured.

Electromechanical alignment method in which the reference line is established by means of a metal string stretched between points P2 and P3. In each of the control points, a special device is fixed, equipped with a container filled with liquid. In the container there is a float attached to the metal string. The displacement of the control point results in the change of the position of the float in the container, recorded by electric sensors and may be transmitted telemetrically to the surveying station.

Laser-alignment method, in which a laser beam stands for the reference line. The target placed at the control point may be manually introduced into the laser beam by means of a micrometric screw and then the displacement value is read out of the micrometer. Another option is an immobile target equipped with a photodetector, which records the position of the laser spot in relation to the centre of the target.

Trigonometric method – consists in taking manifold measurements, at specific time intervals, of horizontal angles and distances, aiming at the control points from the fixed reference points located outside the zone of impact of the structure under survey. The surveying is carried out with the help of theodolites or tacheometers with high accuracy of angle and distance measurement. The ordinates of the control points are calculated by means of manifold computation of angular, angle-linear and linear intersections. The differences of the ordinates of the points under investigation, calculated from the particular measurement cycles, make it possible to count the displacement of those points.

3. Experiences with side force load tests

The first object under test was a driven concrete pile with the length of 13 m, submerged into medium-compact and compact non-cohesive soils and firm clays. The pile group was formed to carry the loads from a bridge pillar. Due to the fact that the horizontal bearing capacity was difficult to estimate, the criterion for the scope of the survey was assumed as the moment when the lateral displacement of a pile exceeds 15 mm. It must be stressed that in the case of foundation piles, their lateral load capacity equals the force by which the pile's displacement amounts to 10 mm. The structure of the reference base to which the dial gauges with the accuracy of 0.01 mm were fastened, was deployed on the adjacent precast concrete piles at the axial distance of about 1.2.m from the pile under the test load. Control geodetic survey was carried out by means of the alignment method and included the readouts with the THEO 020 theodolite from a rule with the imprinted millimetre scale. The reference points were stabilized at the distance of about 6 m from the pile under test. The pile's displacement was measured by means of both methods, at the height of about 40 cm above the ground (see Figure 3). Figure 4 presents the results of horizontal displacement.

Figure 3. The surveying station for testing lateral load capacity of precast concrete piles

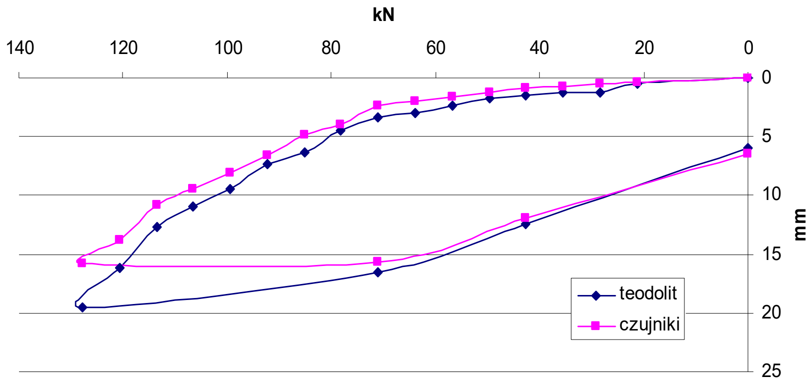

Figure 4. Graph of lateral displacement observation (red – dial gauges, blue - theodolite)

It is noteworthy that the survey carried out by means of a geodetic method revealed greater values of horizontal displacement, which undermines the validity of the "independence" of the reference base with the dial indicators. Moreover, the value of the displacement after unloading was larger in the case of the measurement using the sensors. That means that the adjacent piles which formed the framework for the reference beam with sensors were subject to permanent displacement during the test.

4. Lateral tests in a slope – layout and results

The subsoil around the piles consisted of medium and coarse sands with the density index I_D>0.67. The load tests were conducted with the help of an actuator (hydraulic jack) which strutted two piles in the pile foundation at the level of their heads: the 40×40 cm pile was loaded with a lateral force directed towards the slope of the embankment, the 25×25 cm pile was loaded with a horizontal force directed towards the roadway (see Figure 5 and Figure 6).

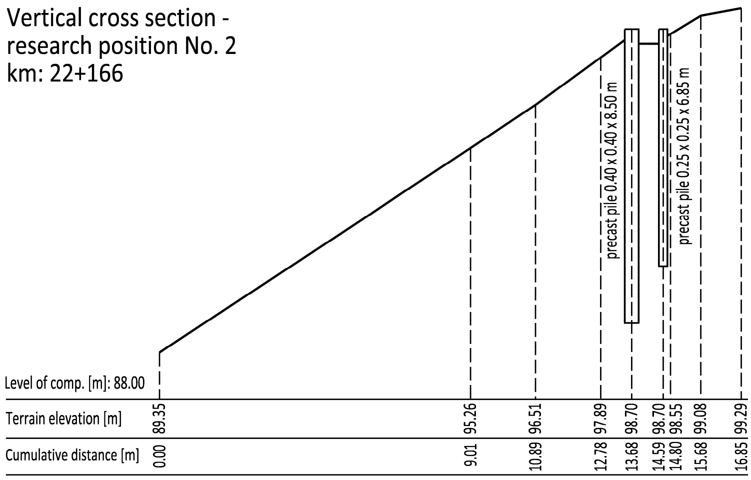

Figure 5. Typical layout of piles in the slope

Figure 6. Horizontal loading –independent surveying control

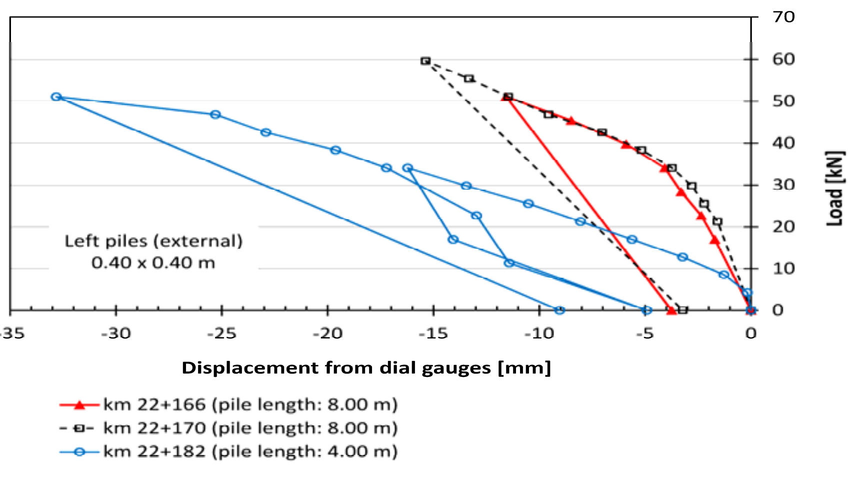

Figure 7. Broken piles deflected 2-5 times more during the test

In general, one could observe on Figure 7, that broken piles deflected during the test 2-5 times more than the integral ones. The load test was done in subsequent cycles of a service load and during overloading. The main goal of the test was estimating of the lateral pile stiffness and evaluation of number of cycles required for stabilization.

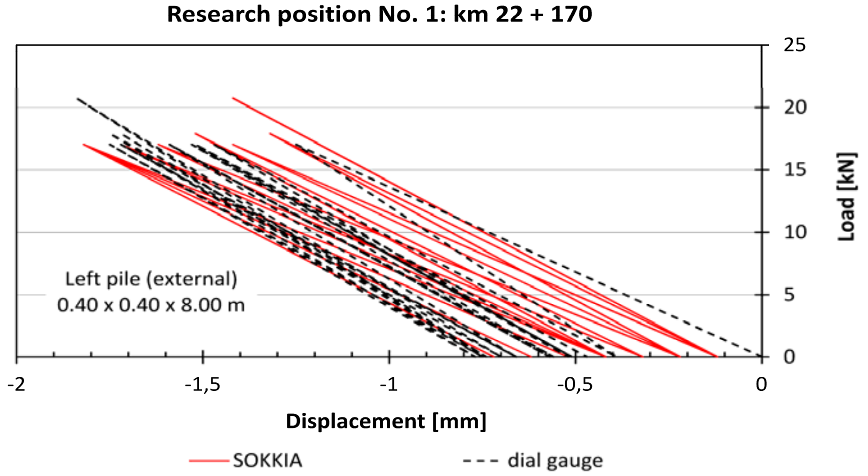

Figure 8. Load - displacement graph in subsequent load cycles within a service load range

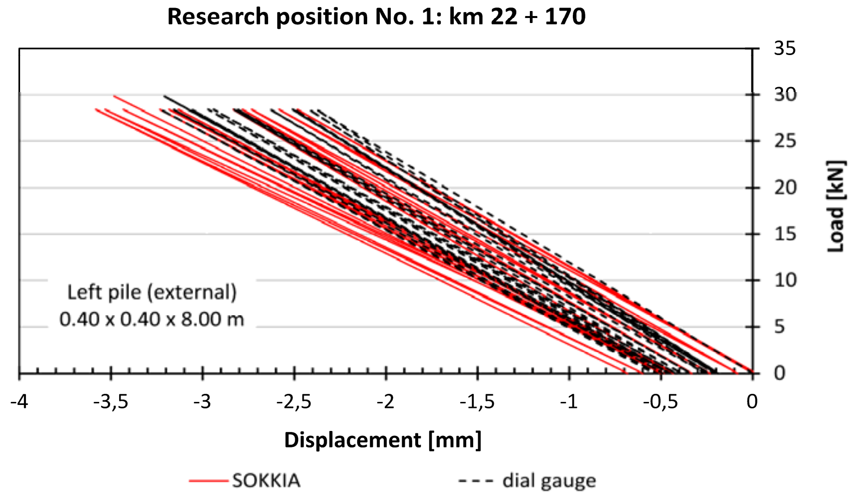

Figure 9. Load - displacement graph in subsequent load cycles during overloading

Obtained results, printed on load - displacement graphs (Figures 8, 9 and 12) confirm the suitability of surveying methods providing comparable accuracy of measured test results. Such conformity was reported in previous works of he authors [3] and recently by Baca et al. [9]. The horizontal stiffness, understood as the relation between the applied load increment and displacement increment (formula 1), can be defined in the subsequent steps of load test (see Figures 10 and 11).

$$K_x = \frac{dQ}{dx} \tag{1}$$

Figure 10 and Figure 11 show the changes of horizontal pile stiffness in the course of cyclic loading. One may noticed that within service range of load the stiffness tends to stabilize after 4-5 cycles (8-10 steps of reloading and unloading). When the applied load is too big (Figure 11), the horizontal stiffness tends to decrease after each cycle.

The observed behaviour of driven pile subject to lateral load was than confirmed by further load tests and monitoring of the structure. Seven years after works completion, the acoustic barriers based on tested piles do not show any sign of damage.

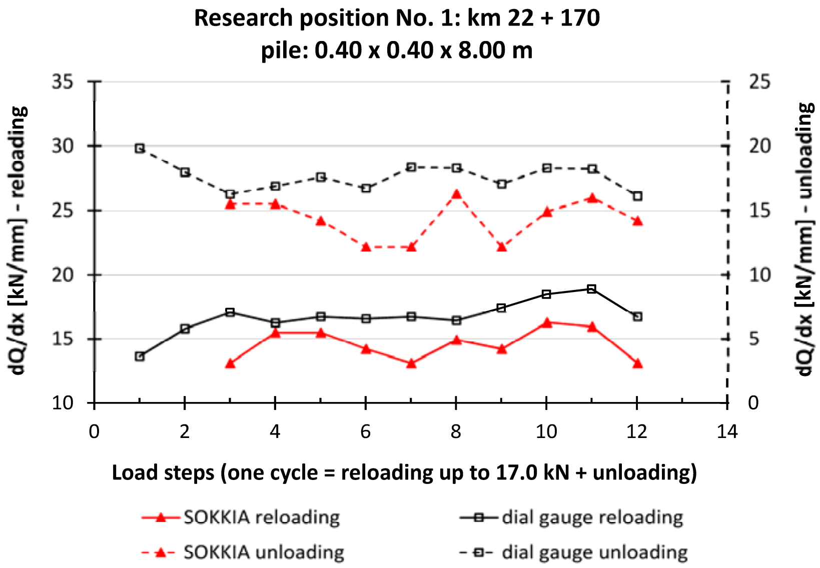

Figure 10. Graph of horizontal stiffness at 17 kN (service load) unloading – reloading cycles

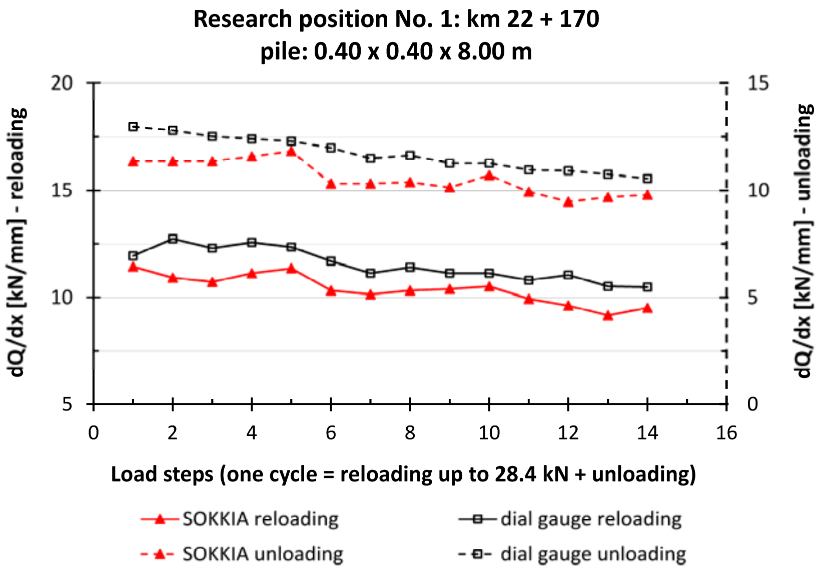

Figure 11. Graph of horizontal stiffness at28 kN (overloading) unloading – reloading cycles

5. Basic conclusions

The ongoing research conducted at Wroclaw University of Technology made it possible to collect, compare (Figure 12) and summarize the results of displacement measurements in course of static load testing of driven piles. Collected results provide important information concerning horizontal stiffness of driven piles in the slope. Some selected case studies of cyclic loading in horizontal (lateral) pile load tests presented in the paper form the point of departure for reliable numerical studies on the basis of a 3D FEM model of soil. The calibration of soil parameters for selected constitutive models may be the next step of the analysis. The presented results are of primary importance for pile design methods.

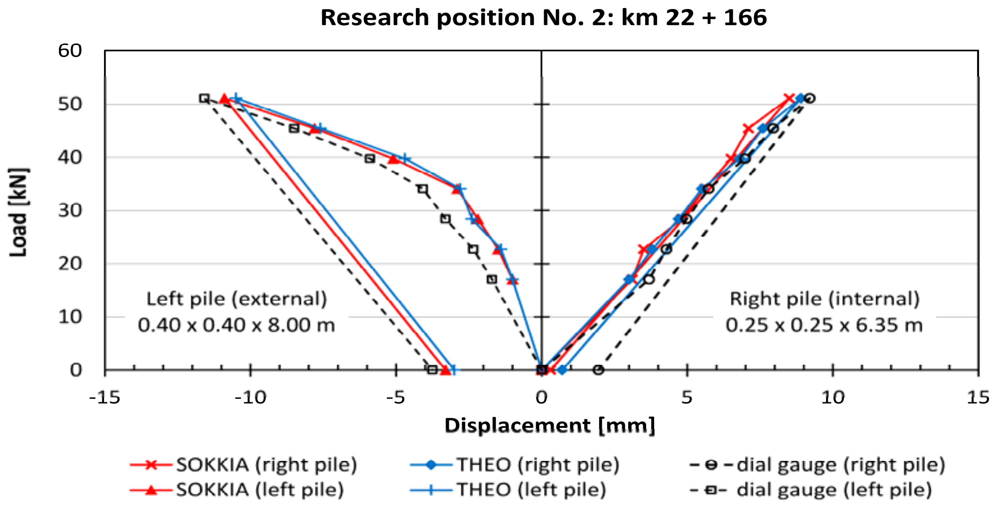

Figure 12. Comparison of various displacement measurements

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