Field Test of Driven Pile Group under Lateral Loading

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Abstract. All the geotechnical works need to be tested because the diversity of soil parameters is much higher than in other fields of construction. Horizontal load tests are necessary to determine the lateral capacity of driven piles subject to lateral load. Various load tests were carried out altogether on the test field in Kutno (Poland). While selecting the piles for load tests, different load combinations were taken into account. The piles with diverse length were chosen, on the basis of the previous tests of their length and integrity. The subsoil around the piles consisted of mineral soils: clays and medium compacted sands with the density index ID>0.50. The pile heads were free. The points of support of the “base” to which the dial gauges (displacement sensors) were fastened were located at the distance of 0.7 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 displacement of the piles subject to the load tests was carried out (by means of the alignment method). The trial load was imposed in stages by means of a hydraulic jack. The oil pressure in the actuator was corrected by means of a manual pump in order to ensure the constant value of the load in the on-going process of the displacement of the pile under test. On the basis of the obtained results it is possible to verify the numerical simulations of the behaviour of piles loaded by a lateral force.

1. Introduction
Pile foundations carrying vertical (axial) loads are necessary to support large structures when the grounds (geotechnical conditions) are not strong and stiff enough to support the structure. Deep foundations (mainly piles and columns) can be embedded in bearing layers (dense sands, hard clays, rocks) at depth. Additional frictional support to help resist vertical loads is mobilized along piles shafts along their length. Methods of axial testing of piles capacity are widely discussed in literature and standardized in Codes of Practice. The transmission of lateral loads is however usually considered of secondary importance as the horizontal loads in the most cases are relatively small. For a large class of building structures like: towers, acoustic screens and wind turbine masts, lateral forces are just as important as vertical loads. Lateral loads are usually imposed by wind and water or earth pressures. More serious lateral actions occur as a result of unpredicted natural hazards such as slope failure, and lateral spread induced by liquefaction and finally by paraseismic and seismic events like earthquakes. Whenever severe requirements concerning lateral displacements are considered in designing of pile foundations, the evaluation of such deflections is often even more complicated. The most reliable solution is than trial testing in natural (technical) scale and referring to previous experiences. Presented load tests were carried out altogether on the test field in Kutno (Poland).
2. Theoretical approach to lateral resistance

Lateral pile response to an imposed horizontal load is described by developing a relationship between the deflection of the pile and the resistance for every soil layer. This formula is represented graphically by so called “p-y curve”, where $p$ represents the soil resistance per unit length of the pile and $y$ represents the lateral displacement respectively. Each soil layer will have a different resistance depending on the depth, principal stresses and strength of the soil, and therefore a different $p$-$y$ curve must be established in the form of non-linear springs. The pile is usually modelled as a beam loaded at the free (for rotation) pile head by the given lateral load. It is important to mention that various methods of modelling horizontal deflections considering two dimensional or cyclic loading were proposed, but anytime the results are valid for the particular case. Another week point of computational models based on $p$-$y$ curves is their limitation to single pile analysis. In practice, piles are very rarely isolated. In most of the real cases, piles are composed into pile-groups with a common capping beam or slab in order to strengthen their stiffness and load resistance.

Recently, numerical modelling by means of the finite difference method or finite element method with pile-soil interaction model makes it possible to calculate deflections and reactions along the length of the pile. It must be emphasized that the lateral loading must be modelled in 3D (three dimensions). That makes it far more complicated and time consuming than ordinary axial (vertical) analysis which can be performed in 2D (two dimensional) models. Although, in most of the cases, a pile-group strengthens overall lateral load resistance, the resulting pile group lateral capacity is not a simple sum of the unitary resistances. The developing of plastic zones in front of the loaded pile can seriously weaken the individual pile response of the single pile members of the group. The overall lateral load is non-uniformly divided among each of the piles in the group as each pile pushes against the soil creating a shear zone. Those shear zones begin to enlarge and overlap as the lateral load increases. The overlapping occurs mostly when the piles are spaced very closely together. When overlapping occurs between two piles in the same line it is called “edge effects” and when overlapping occurs between piles in adjacent rows it is known as “shadowing effects.” All of those “group interaction effects” result in reduced horizontal resistance of a single pile.

That phenomena usually lead to a conclusion that in most of the cases the leading row of piles has the highest resistance because it only experiences edge effects. The piles in the leading row are therefore only slightly less resistant than a single isolated pile under the same loading. The piles in the other rows have even lower resistance because they experience edge effects and shadowing effects. The gaps that form behind the piles also assist in decreasing the resistance of the piles behind them. That intuition may however be misleading in the case of driven piles, where the above mentioned factors are compensated by increased density of the soil inside the pile group. Some remarks concerning this effect can be found in work [1].

The existing research that has been done on laterally-loaded piles and pile groups can be divided into three general categories:

- Full–scale tests of single piles and pile groups. Starting from work of Feagin [2] through rapid development of computer methods in last two decades of the last century resulting with works of Reese et al. [3], Puła and Różański [4], Kim and Brungraber [5], Brown et al. [6], and other authors [7-10], who concentrated mainly on group effects. All these are tests were done on full-scale piles and pile groups. Such tests are the most accurate because they simulate actual conditions. They are also the most expensive and the most difficult to perform with regard to their unique character and law representativeness for other cases. In general, most of the authors confirmed what had already been observed by Feagin [2] that group effects increase with larger deflections. Kim and Brungraber [5] observed that front row piles had greater resistance and also developed greater moments for a given pile group deflection. Ruesta and Townsend [9] performed full-scale tests in sand in order to compare results with full-scale tests done by Brown et al. [6] and centrifuge tests done by McVay et al. [11]. The tests conducted by Ruesta and Townsend [9], were the first full-scale tests to have more than three rows and were unique in that they had four piles in each row. The piles were much larger than in other tests
and were reinforced. Other results were presented by Rollins et al. [12], who compared measured and computed lateral responses. Much attention has also been paid to study the effects of spacing in laterally loaded pile groups and how the pile spacing affects lateral resistance of the piles.

• Small-scale tests by means of model tests and centrifuge tests. The centrifuge exposes the model to high acceleration fields so that the model can better represent the actual soil stresses of a full scale test. Kotthaus et al. [7] used a centrifuge and small aluminium piles to conduct tests that simulate prototype concrete piles in sand. Kotthaus observed that row efficiency decreased with trailing rows, defining efficiency as the ratio of the group load to the single pile load. McVay et al. [8] discovered that the pile spacing was much more influential on pile group interactions than the density. Such small-scale tests are much cheaper than constructing a full-scale test and can be repeated and modified easier. The result however, must be treated cautiously due to the scale effect.

• Numerical modelling – This type of testing uses computer algorithms and equations to solve lateral-load problems. This is the least expensive type of testing but also the most difficult to represent actual conditions. Interesting developments were juxtaposed in work of Kozubal et al. [13,14].

Recently, a big attention is paid to “nonstandard” cases like laterally loaded piles in the slope or pile exposed to horizontal cyclic loading. The first issue is recently developed at Wroclaw University of Science and Technology and already presented in works of Rybak and Muszynski [15,16]. Cyclic loading applied to large pile groups was described by Brown et al. [17]. Some remarks concerning repeated and cyclic lateral loads and their developing lateral stiffness were also given by Rybak [18]. Very sophisticated, experience supported computer modelling of cyclic bidirectional lateral loading of single pile was published by He et al. [19].

3. Undertaken research program – field conditions and testing procedure
The pile group was laterally loaded and instrumented to collect deflection, load, and strain data. A separate single pile was similarly instrumented and tested for comparison to the pile group. The soil profile was built of a top layer of sand about 2.5 meters deep underlain by alternating layers of fine grained soil and sand. Analysis was done in order to determine $p$-multipliers for the rows in the pile group. Not surprisingly, group effects were more significant at greater loads with larger deflections. Higher deflection caused increased shear zone interaction and a decrease in lateral resistance. There are still some other factors concerning laterally loaded pile groups that require further investigation. One factor concerns the influence of greater spacing on pile interactions, and the exact spacing to which the group effects become negligible. So far, Remaud et al. [10] found group effects to be negligible for spacing greater than 6 pile diameters; however, Rollins et al. [12] concluded that this spacing depended on the row location and varied between 5 and 8 pile diameters.

3.1 Geotechnical conditions
A vast amount of geotechnical site information was available because of the various testing that has been formerly done on this site. Geotechnical investigation was performed in the immediate area surrounding the tested piles. The field test was made in mineral soils: clays and medium compacted sands. In-situ tests conducted consisted of CPT tests and drilled holes. The soil conditions and basic geotechnical parameters are juxtaposed in Table 1. Water table is 2.2 m below ground surface.
Table 1. Soil conditions

| Thickness [m] | Soil            | Unit weight [kN/m³] | Friction angle [°] | Cohesion [kPa] |
|---------------|-----------------|---------------------|-------------------|---------------|
| 2.5           | Medium Sand     | 17                  | 34.5              | 0             |
| 2.3           | Medium Sand     | 20                  | 37                | 0             |
| 1.0           | Fine Sand       | 19                  | 32.5              | 0             |
| 0.4           | clay            | 20.5                | 22                | 35            |
| 1.8           | fine/silty sand | 20                  | 33.3              | 0             |
| 0.8           | Medium Sand     | 20                  | 34                | 0             |
| 2.7           | silty/fine sand | 20                  | 33.6              | 0             |
| 1.0           | sandy clay      | 22                  | 24.5              | 42            |
| 4.5           | sandy clay + gravel | 22.5          | 27                | 49            |

The locations of the in-situ soil investigations done in relation to the location of the pile groups are presented on figure 1.

Figure 1. Locations of in-situ tests (CPT, borehole)

3.2 Field test conditions and equipment
The pile heads were free. The points of support of the “base” to which the dial gauges (displacement sensors) were fastened were located at the distance of 0.7 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 displacement of the piles subject to the load tests was carried out (by means of the alignment method). The trial load was imposed in stages by means of a hydraulic jack. The oil pressure in the actuator was corrected by means of a manual pump in order to ensure the constant value of the load in the on-going process of the displacement of the pile under test. The scheme of pile localization and the layout of three groups of precast piles which were chosen for the test is shown on figure 1. Two groups consist of two piles: ST1 – pile numbers K17 and K22; ST2 – pile numbers T08B and T08C and one of three piles: ST3 – pile numbers K19, K20 and K21.

The research stands were selected as follows. At research stand ST1 piles were in close proximity to each other – 2.5m – to determine the impact of the stress zones in front of the piles. The ST2 stand piles were at a great distance – 6.3m – so that this impact is not observed. The third ST3 research stand was designed in order to determine how does the load on the individual piles in the pile group was distributed. The load was transferred to the individual piles in a flabby way - using a micropile rod, and the heads were free during the test. The load was transferred from the hydraulic jack.

The piles were attracted to each other in the case of ST1 and ST2. In the case of ST3, piles K19 and K20 moved in one direction and the reacting K21 in the opposite direction.
Measurement of the force distribution was done by using a pressure cell mounted on the K20 pile. The distribution of forces directly depends on the tension of the rod through which the load is transmitted. Measurement of displacement was made using the dial gauges. They were mounted on the head of each pile on the independent reference frame structure, which provided absolute measurements, and sensors were also mounted measuring the relative displacement of the ground in front of the pile in the distance of 0.5m. In the case of stand ST2, additional dial gauges were placed on a pile head at 70cm above the lower one to check the inclination of the free pile head. This measure allowed it to determine its turnover.

The measurements of the displacement of the pile heads were made using the theodolite alinometric method. However, their accuracy compared to the dial gauges was very small. Inclinometric measurements were performed at the ST3 station. The measuring tube was 1 meter in front of the K21 pile. Values are measured too low and do not exceed the measuring error of the device. Which means that the range of influence was smaller than the location of the measuring tube. Piles were previously tested with a static test load.

**Static Load Test No. 1 – short distance**

The T08B and T08C piles 40×40×1600 were loaded. The load was applied in steps at 6 kN. Then the piles were unloaded. Three load cycles were carried out. First up to 90kN, two next up to 120kN. The hydraulic jack was located at the T08C pile. Four dial gauges were used for displacement control: I on the T08B, II in front of the T08B, III on the T08C and IV in front of the T08C.

![Figure 2. Layout of first coupled static load test (piles T08B and T08C)](image)

It must be underlined that the internal capacity of the piles was provided at every step of the test. The piles were reinforced by 8 steel bars of diameter 32mm which is one of the stiffest in the catalogue of precast piles for the impact driving. Figure 3 presents detail of T08B pile with the layout of dial gauges and scales for the alinometric method of displacement control.
Static Load Test No. 2 – long distance

The K17 and K22 piles with dimensions 30×30×1500 were loaded. The load was applied in steps from 7.5 kN to 105 kN. Then the piles were unloaded. Load cycles were repeated twice. The hydraulic jack was located at the K22 pile. The dial gauges were placed: I high on the K17 pile, II low on the K17, III in front of the K17, IV high on the K22, V low on the K22 and VI in front of the K22. The tested piles K17 and K22 were reinforced by 4 bars of 32mm and 8 bars of 25mm respectively.
The layout of dial gauges fixed to independent reference frame made it possible to measure the inclination of pile head in course of loading. The sensor based on the steel pipe measured the relative displacement of the pile and the soil wedge in the passive zone (in front of the loaded pile).

**Static Load Test No. 3 – Triple Test**

The piles with dimensions: K19 40×40×1400 reinforced by 8 bars 20 mm, K20 and K21 40×40×1800 reinforced by 8 bars 32 mm were loaded. The load was applied in steps from 20 kN to 100 kN. Then the piles were unloaded. The hydraulic jack was located at the K21 pile and the pressure cell at the K20 pile. The dial gauges were located only on the pile heads.

![Figure 5. Layout of triple static load test (piles: K19, K20 and K21)](image)

The construction of testing appliance enabled for a continuous control of load and displacement of the whole pile group.

**4. Measurements results and analysis**

Figures 6, 7 and 8, show the diagrams of the displacement of the pile heads. They move nonlinearly. With the repetition of load cycles, the displacement values also increase. At the end of the load cycles, the heads return to their original position after the relatively short time. In all the cases, the ultimate lateral capacity was not reached. It would be necessary to increase the load value to determine the load capacity but, due to the agreement with the company providing the research field (Aarsleff) such charges were not implemented to enable for further testing.

**4.1. Results of the cyclic loading of piles in SLT No.1**

In both cases (pile T08B and pile T08C), it can be noticed that the relative displacement measured in front of the loaded pile are significantly smaller than the absolute displacement. That confirms previous studies [1] concerning the necessity of the independent reference system or the use of
surveying techniques. Interesting remarks concerning methodology of displacement control in geotechnical testing were juxtaposed by Muszyński in work Chyba! Nenašiel sa žiadny odkaz., which was related to the accuracy of horizontal displacement control of hydraulic structures.

Figure 6. Results of coupled static load test (a) pile T08B and (b) pile T08C.

Figure 7. Results of coupled static load test (a) pile K17 and (b) pile K22.

4.2. Results of the repeated loading of piles in SLT No.2
The measured results are graphically presented on above figure 7 (a) and (b) for the piles K17 and K22 respectively. Left graph: sensor I is at the top of the pile head, while III at the bottom a II measures relative displacement. Very small difference may be observed in displacement values on sensors II and III, which means that the ground in front of the pile moves with it. Sensor II is in the direct impact zone.
Right graph: similar situation occurs for pile K22. The sensor placed high IV on the pile head indicates much greater displacement than the sensor located below VI. Also sensor V is in the direct impact zone.

4.3. Results of the repeated loading of piles in SLT No. 3

The load distribution in the pile group during the test is shown on the load-displacement chart (figure 8). The pile head K19 undergoes greater displacement. There may be two reasons for this: it is a shorter pile with smaller number of reinforcement bars or by accepting a higher load on it. K20 pallet - greater share of load distribution (depends on the tension of the load system).

![Figure 8. Results of coupled triple static load test (piles: K19, K20 and K21)](image)

5. Conclusions

The limited range of the test, caused by the further plans of vertical examination, prevented from reaching the ultimate lateral capacity. It was confirmed that the influence zone in front of the pile did not change the test results, however it must be considered in the planning of Static Load Testing. On the basis of the obtained results it is possible to verify the numerical simulations of the behaviour of piles loaded by a lateral force. The authors will check the suitability of various soil constitutive models in modelling the behaviour of laterally loaded piles. The presented work forms just the basis for further calibration.

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