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# **Numerical model of the ‘pile – subgrade’ system loaded with horizontal force**

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## **1 Introduction**

Pile foundations are classified as deep foundations applied on land and in the sea. They are mostly employed for transmission of significant loads onto the deeper, load-bearing and rigid layers of ground.

Calculations for pile foundations are carried out to determine the internal forces (within the pile and in the pile cap construction) as well as displacements and deformations of the entire pile system. Such calculations pose numerous difficulties, mainly due to a three-phase character of the subgrade and its non-linear work in the range of load – settlement / displacement.

The calculation of piles loaded with a horizontal force remains to be an important and difficult issue, not yet well recognised.

## **2 Calculation of piles loaded with horizontal force**

There is a broad array of methods in geotechnical engineering which can be used for designing piles loaded with a horizontal force, in particular, acc. to: Brinch Hansen (1961), Broms (1964, 1965), Kosecki (1988), Poulos (1971, 1972), Reese and Van Impe (2001). The results obtained according to such proposals often differ, however, e.g. Gawlik (2016), Ruigrok (2010). This derives from considerable simplifications and limitations, which allow to evaluate, with different accuracy, the interworking of the pile system with subgrade.

The most reliable design method of piles acc. to Eurocode 7 (1997) are test static loads. They can be conducted by two methods: the method of maintained load steps (SM and QM tests) and the method of constant rate of penetration (increment) (CRP). Their results set a basis for preparation or verification for empirical or analytical methods. On the other hand, the results of static test loads can be confirmed by analytical methods or by numerical analysis.

Numerical methods have grown in importance in the recent years due to advancement of computer technology. They are employed especially for solving complex constructional systems. One has to be aware, though, that to obtain measurable results - apart from an appropriate static scheme, selection of constitutive ground models and modelling a contact zone between a pile and ground - parameters of the chosen models have to be selected, as well.

The article presents a numerical FEM model of a “pile – subgrade” system loaded with a horizontal force, the basis of which were the results of the undertaken field investigations. Constitutive models in the form of a linear elastic model (pile) and elastic – perfectly plastic Mohr-Coulomb model (subgrade) were applied for calculations. The parameters of the mentioned models were calibrated based on laboratory tests, geotechnical documentation and a standard. The model was verified by comparing the results of FEM calculations with the results of field investigations.

### **3 Field investigations**

Field investigations were performed at one of the construction sites in Siemianowice Śląskie during construction of a palisade securing a deep trench.

The palisade consisted of 92 reinforced CFA piles with a total length of 45.5 m. The top of the palisade was designed as a reinforced concrete cap with a width of 0.6 m and thickness of 0.5 m, joined monolithically with a reinforced concrete 0.2 m face wall.

#### **3.1 Ground conditions**

Ground and water conditions in the region of the investigated pile were identified based on geological and engineering documentation and own investigations. The subsoil of the investigated area is formed by Quaternary formations represented, in the bottom part of the profile, by deposits of a river and marginal accumulation, in the form of fine and medium sands (FSa, MSa,  $I_D=45\%$ ), covered with a series of dusts and silty clays (Si, cISi,  $I_c = 0,90$ ).

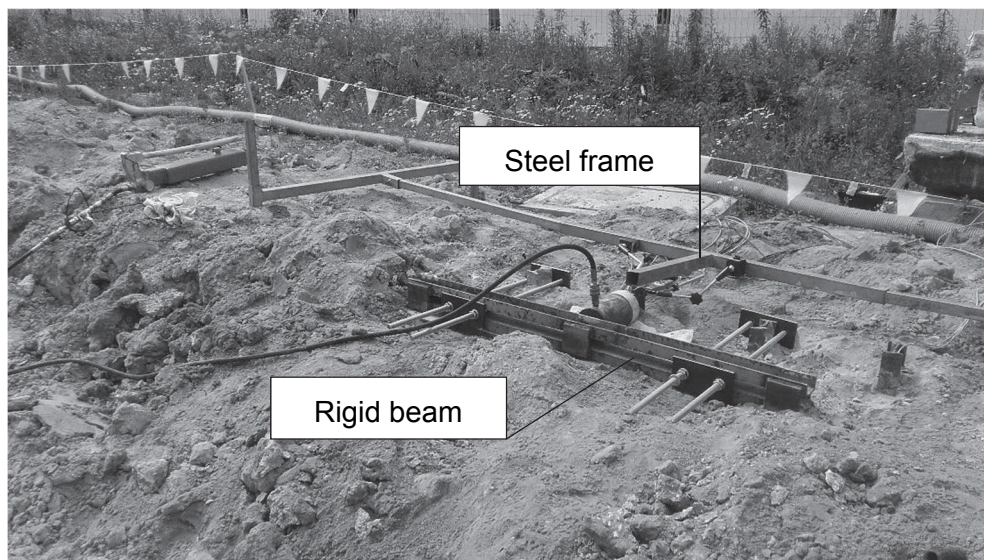
#### **3.2 Test load of the “pile – subgrade” system loaded with horizontal force**

One of the palisade piles was subjected to a test load with a horizontal force. The pile was installed as driven (CFA), with a diameter of 0.4 m and length of 5.0 m, reinforced with a steel IPE 100 section (S235 steel). C20/25 XC2 concrete was

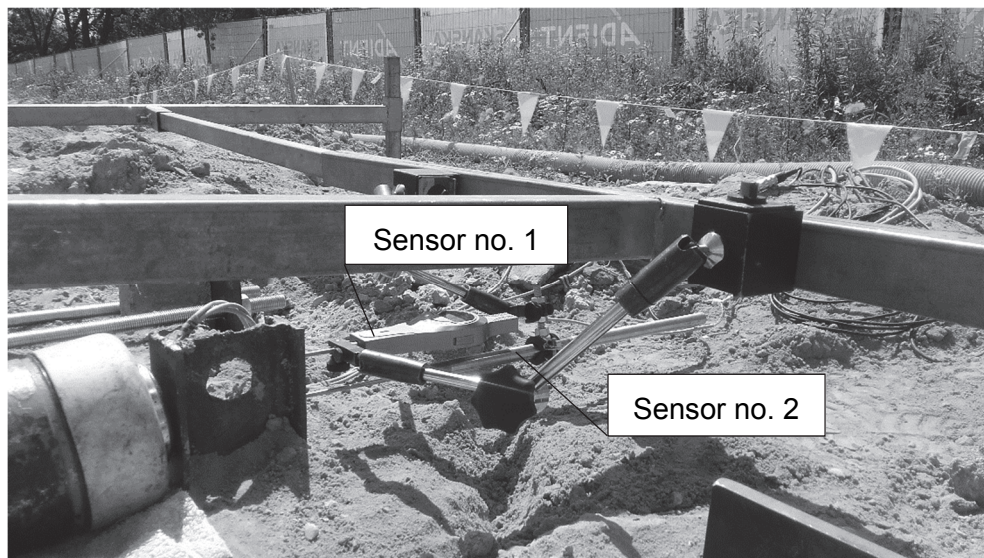
used to produce the pile. Pile displacements and steel section deformations were examined during the investigations.

The first part of the measuring system was a rigid beam (two welded channel steel sections with a length of  $\sim 1.6$  m), against which a hydraulic jack was supported. The steel beam was supported against two adjacent piles with a bolt joint ( $\phi 20$  mm threaded bars) (Fig. 1).

A load was generated with a single-acting SPX 30 t hydraulic jack. A piston rod was applied to the protruding reinforcement of the pile and it was extending under the influence of work of a manual hydraulic pump. Pressure in the hydraulic system was measured with a manometer with the accuracy of 0.1 MPa.



**Fig. 1:** Stand for field investigations – loading system



**Fig. 2:** Stand for field investigations – measuring system

Sensors recording displacements of the investigated pile were mounted to an independent steel frame outside the interaction reach of the loaded pile.

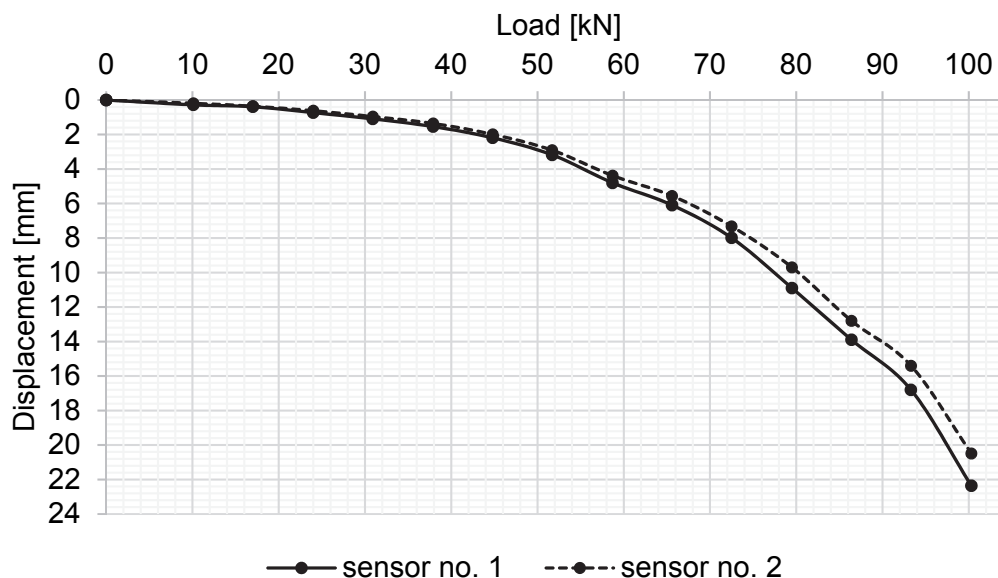
Displacements were recorded in two points. The first, electronic digital sensor (hereinafter called sensor no. 1) was applied to the pile in the location where the force was applied; the other, induction sensor (hereinafter called sensor no. 2) was applied 50 mm lower. The measurement of displacements in the function of force was read every 2 minutes from sensor no. 1, and measurement for sensor no. 2 was done continuously. Measurement was carried out with the accuracy of 0.01 mm. The measuring system is shown in Figure no. 2.

Three TFs–10/120 extensometers with  $120\ \Omega$  resistance, spaced every  $\sim 1.5$  m, were installed on the shelf (at the side of the force applied) to measure deformations of the steel section. The first extensometer was 1.5 m below the force applied. The extensometers were connected to measuring equipment via conductors. Measurements were performed with the accuracy of  $0.0001\ \mu\text{m/m}$ .

Loads were generated with 1 MPa steps, corresponding to the force of  $\sim 6.9$  kN. A precondition for applying another load/unload step was the agreed stabilisation of displacement of  $\Delta y \leq 0.05$  mm over 10 minutes. The investigation was carried out until the pile was losing its bearing capacity.

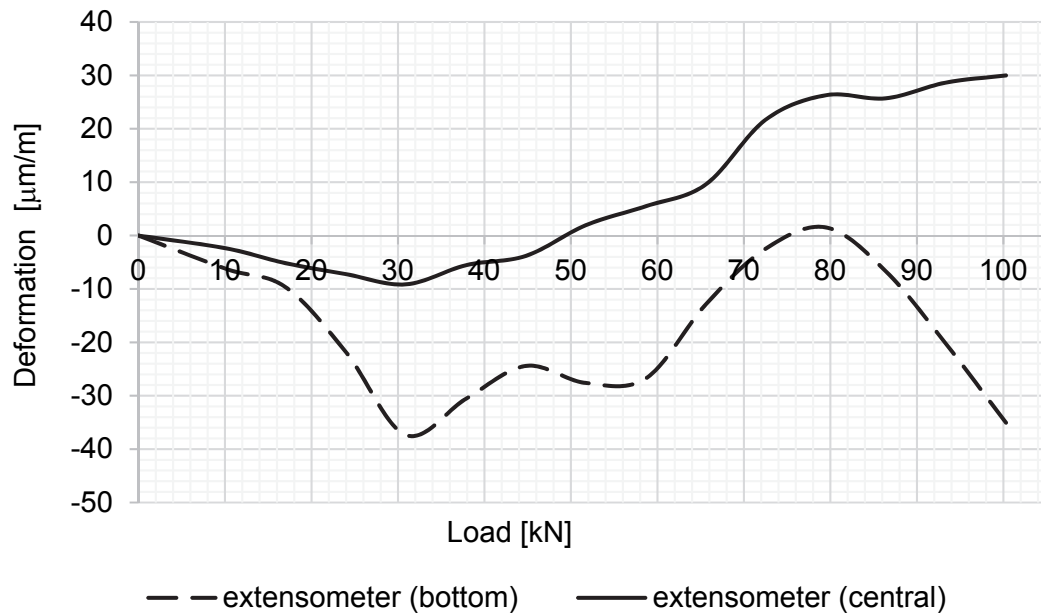
### 3.3 Investigations results

Figure no. 3 shows a chart of the “load – displacement” dependency in the points of applying the measuring sensors: the first (no. 1) in the point of force application (piston rod), the second (no. 2) 50 mm below.

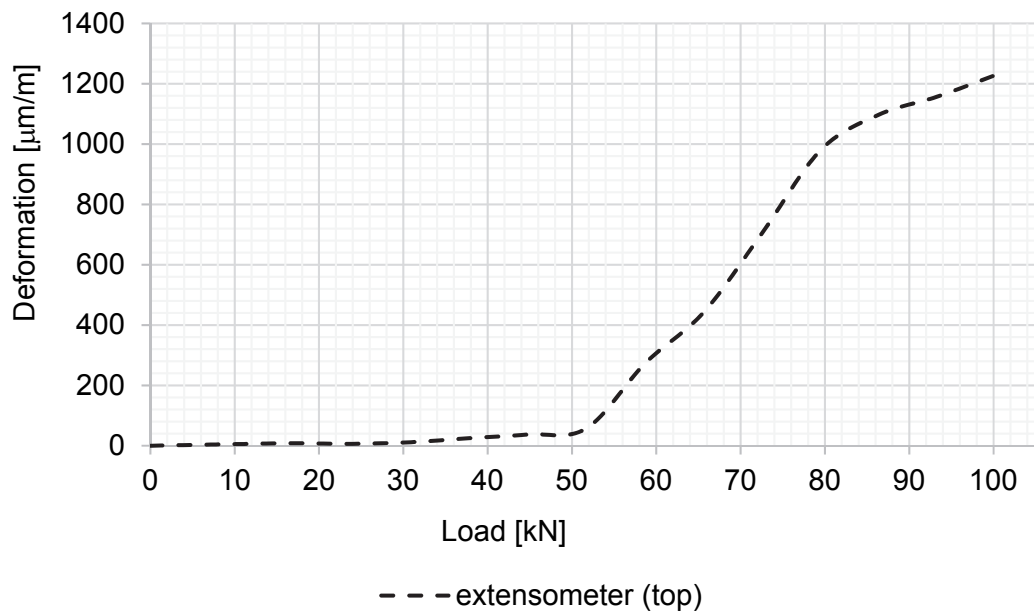


**Fig. 3:** Load – displacement dependency chart, field investigations

Figures nos. 4 and 5 show the results of tensiometric measurements



**Fig. 4:** Tensometric measurements – bottom and central extensometer



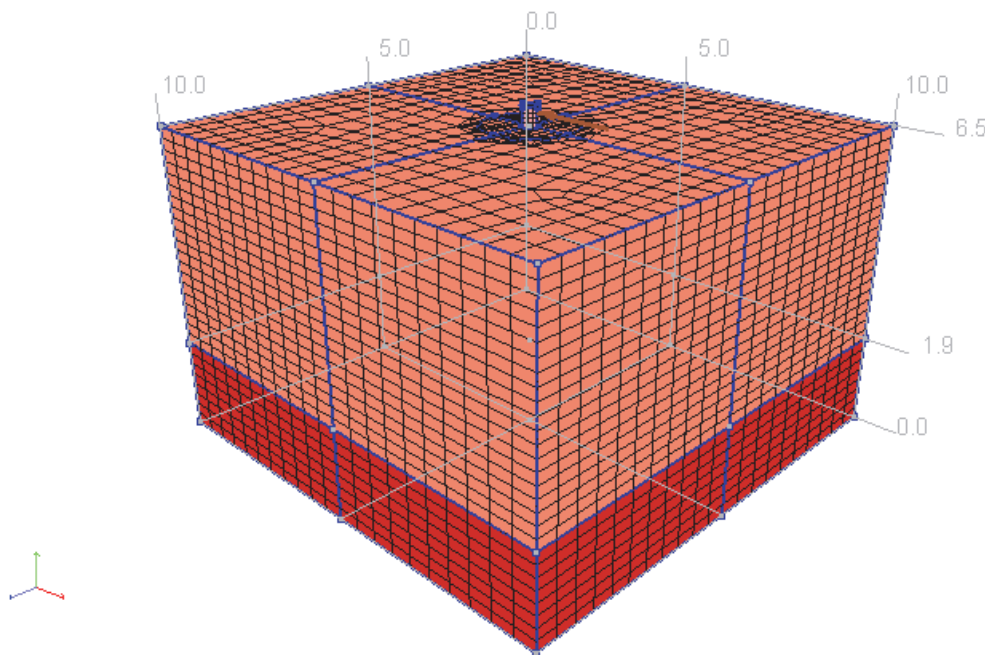
**Fig. 5:** Tensometric measurements – top extensometer

## 4 Numerical analysis

An attempt to create and verify a numerical model with the FEM method was made based on the results obtained in situ. Z-Soil 2011 v11.15 software was used in the analysis.

### 4.1 Calculation model

Figure no. 6 shows a 3D model of a single pile loaded with a horizontal force. A spatial model was built with the dimensions of 10 m in longitudinal direction  $X$  and lateral direction  $Z$  and 6.5 m in vertical direction  $Y$ . The analysis reflects the pile length (5 m) and diameter (0.4 m). The section reinforcement was modelled as a beam element with the set cross-section. Standard boundary conditions were defined on external surfaces of the model. The stage of pile formation in the ground was also considered. A horizontal force was applied to the head of the pile in steps, according to the programme of field investigations. The ground medium consists of two layers. The top layer, with a thickness of 4.6 m, consists of silty clays, and the bottom layer, with a thickness of 1.9 m, of medium sands.



**Fig. 6:** 3D calculation model of pile loaded with horizontal force

A constitutive model of ground was adopted as a perfectly elastic–plastic model with a Mohr-Coulomb failure area. The pile with reinforcement was modelled as a linear elastic pile.

The parameters of the constitutive model, simulating the work of silty clay (cISi), were adopted based on laboratory tests performed with soil samples taken directly

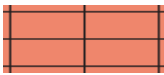

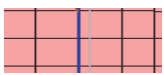
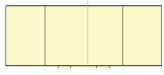

from the place of field investigations. The tests included oedometric and direct shear tests.

Parameters for medium sand (MSa) were adopted according to geological and engineering documentation. Material properties for concrete and steel were however adopted based on Eurocode 2 (2008) and Eurocode 3 (2006).

Contact elements were applied to describe discontinuities of displacements at the pile-subgrade contact point and to model the friction between the ground and the pile. It was assumed as per PN-83-B-03010 standard that a ground-to-pile friction angle value equals the two-third of the internal friction angle of the ground surrounding the pile.

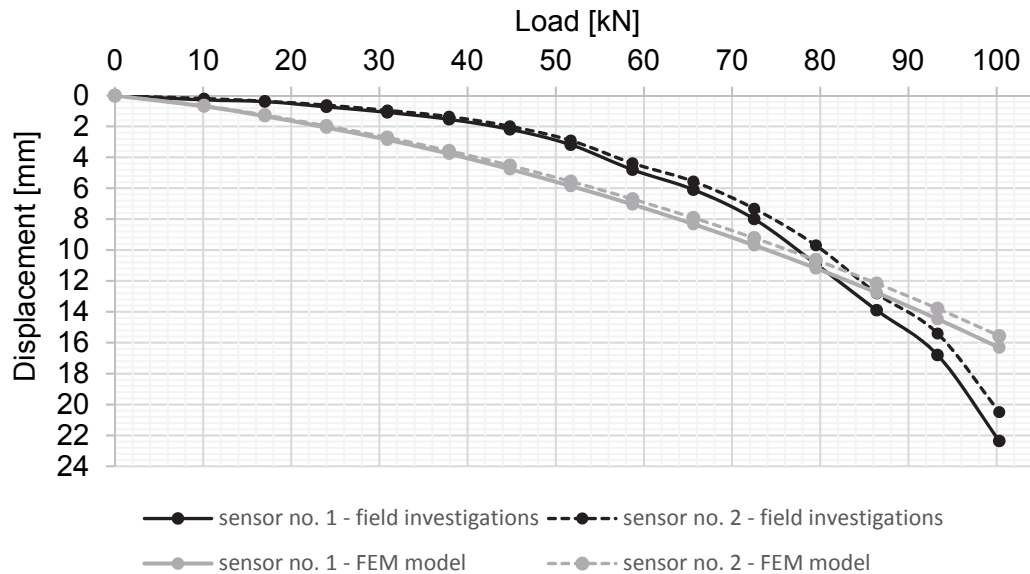
Table 1 lists parameters of constitutive models determined and adopted for calculations.

**Tab. 1:** Values of material parameters of particular elements of the system

Layer	Model symbol	c [kPa]	$\phi$ [°]	$\nu$ [-]	E [MPa]
Silty clay (cISi)		22.2	16.3	0.3	28
Medium sand (MSa)		0	32	0.3	65.9
Pile - concrete		–	–	0.2	30,000
Pile - reinforcement		–	–	0.3	210,000
Contact		0	10.9	–	–

## 4.2 Verification of numerical model

Figure no. 7 shows a chart of the “load – horizontal displacement” dependency in the points of application of measuring sensors, obtained based on the proposed FEM model, together with results of field investigations.



**Fig. 7:** Load – horizontal displacement dependency chart obtained based on FEM calculations and field investigations

The value of the modified determination coefficient  $R^2$  was used as the consistency criterion of results, acc. to Pieczyrak (2001). The coefficient, determining the matching of the mentioned results of the curves, was 0.92, which signifies very good matching. A pile investigated in field exhibits higher initial stiffness in relation to a pile from numerical analysis.

Small differences in results may stem, in particular, from the adopted constitutive model, which well verifies the matter of bearing capacity, but is less accurate in representing soil behaviour prior to the loss of bearing capacity. Moreover, the adopted subgrade construction diagram is not a perfect representation of the real ground structure.

## 5 Conclusions

In order to be able to reflect accurately the work of subgrade under the influence of a load, ground conditions need to be defined and their parameters determined, a constitutive model of ground needs to be selected appropriately and a contact zone between the pile and the ground needs to be modelled.

An advantage of using the Mohr-Coulomb elastic-perfectly plastic model is easy implementation and a possibility of determining its parameters in simple laboratory tests. The analyses performed show that by applying a Mohr-Coulomb model in a FEM analysis, similar results were obtained to those obtained in field, however, pile work differs for a larger load range. This is a consequence of adopting a linear dependency  $\sigma$ - $\varepsilon$  in the model, which in fact is non-linear. The model is classified as the most popular and most commonly used one. It can be

presumed that the use of more expanded models would allow to represent more accurately the load-deformation dependency for subgrade. This is, however, associated with more difficult determination of actual ground measurements and, frequently, with a lack of possibility to use correlation dependencies.

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