CZASOPISMO INŻYNIERII LĄDOWEJ, ŚRODOWISKA I ARCHITEKTURY
JOURNAL OF CIVIL ENGINEERING, ENVIRONMENT AND ARCHITECTURE
JCEEA, t. XXXII, z. 62 (4/15), październik-grudzień 2015, s. 435-446

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SOIL – HYBRID PILE INTERACTION UNDER LATERAL LOAD

The paper presents stability problems of horizontally loaded piles in the three dimensional state of strain. The results obtained are based on works including assessment of interaction between the soil and pile and field investigation of pile as well as on numerical analyses in the spatial system of soil-pile interaction. The author's numerical analysis of hybrid pile shows greater lateral rigidity due to the effective interaction between the pile and soil within a definite range of displacement caused by lateral load. Based on piles embedded in cohesionless soil the phenomena occurring in the soil were identified and a quantitative assessment of the pile displacement caused by Lateral force and bending moment was carried out.

Keywords: numerical modeling, piles, Lateral load, soil-structure interaction, 3D FEM

1. Introduction

In designing piles to resist lateral loads, the design criterion in the majority of cases is not the ultimate capacity of the piles, but the maximum deflection of the piles. To our knowledge, there are very few published methods of analysis specifically developed for predicting the response of piles subjected to lateral loading. To date, it has been customary practice to adopt the techniques developed for laterally loaded piles in soil to solve the problem of laterally loaded piles with caps. A widely used method for lateral load design in a pile foundation is the p-y method. The development of this method was primarily based on work of Matlock and Reese [2]. Their subsequent work led to the development of user friendly computer programs. Reese and Van Impe [4] give a comprehensive description of this method. This method is based on Winkler's spring reaction approach, and it utilizes a beam-column on elastic foundation with nonlinear springs to transfer the load from pile to the soil. These spring represent the soil resistance at different depths and the lateral displacement

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of horizontally loaded pile. Ashour and Norris [1] used strain wedge model to analyze the lateral capacity of the pile. The soil-pile interaction is based on the overlapping passive wedge in front of pile, which is then transformed to an equivalent single modulus of subgrade reaction. Most full-scale loads tests were conducted on free-head piles, but only a few load tests for fixed-head piles have been reported [3]. In these tests, despite the fact that the pile and cap are embedded in the soil layer, the influence of rotation and friction resistance of cap with soils has not been sufficiently evaluated. To completely evaluate the lateral capacity of the pile-soil-pile cap interaction, passive pressure on the pile cap, base friction on the pile cap must be accounted for separately.

2. Description of hybrid structures

A hybrid structure is composed of two combined components; a horizontal one, resting directly on the ground and a vertical one - embedded in subsoil. A foundation constructed that way shows stiffness resulting from the shaft being embedded and the vertical pressure on the ground in front of the pile by cantilever element. The element, appropriately shaped and protruding beyond the shaft outline, works as the cap of the pile head or a few piles in a single row or cap of the heads of slurry walls. Defining the concept of "hybrid foundation" enables a complementary classification of pile foundations with pile caps of different design as well as makes it easier to define their interaction with subsoil [5]. Taking into account the pile cap – subsoil interaction enhances the lateral load capacity of the pile raft foundation. The main effect of the craft is reducing horizontal displacements of the hybrid foundation and the value of the bending moment in the shaft of the pile. Figure 1 shows complementary approach to hybrid foundation forming.

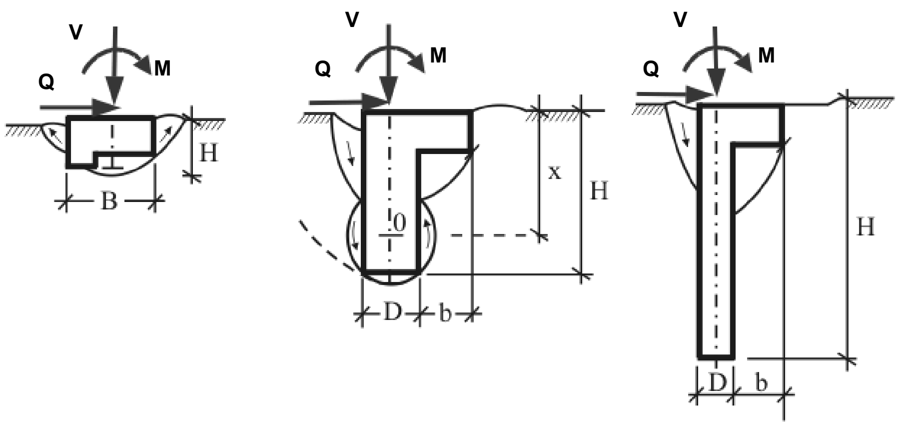

Fig. 1. Complementary approach to hybrid foundations

Rys. 1. Uzupełniające podejście do obliczania fundamentów hybrydowych

The effect of the presented analysis is setting out, based on the author's investigation, the reason for defining the hybrid foundation and describing its nature which consists in transmitting, in a specific way, lateral loads into the subsoil in the spatial soil-foundation interaction system. The research and analyses carried out resulted in a better specification of the current methods of single pile with cantilever plate calculations. An analysis of the spatial soil-pile interaction made it possible to create the basis for a more precise determination of stiffness of the pile with plate. The analysis was performed using the PLAXIS 3D finite element program. To investigate the pile-soil-pile cap interaction, a pile with plate and pile without plate was modeled. The variables employed in this study were the drilled pile diameter 1.2 m, pile length of 5 m. The author's analysis of the single hybrid short pile shows greater lateral stiffness due to the effective interaction between the vertical pile, horizontal plate and soil within a definite range of displacement caused by lateral load. Based on piles embedded in cohesionless soil the phenomena occurring in the soil were identified and a quantitative evaluation of the hybrid pile displacement caused by horizontal force and bending moment was carried out. The use of the cantilever plate results in limiting the horizontal displacement of pile and the reduction of the bending moment of its shaft.

3. Numerical modeling of hybrid foundations

3.1. The numerical model description

Theoretical analysis was carried out by the Finite Element Method (FEM), with the use of the Plaxis 3D computer program. The assumed spatial numerical model of the hybrid pile embedded in subsoil consists of over 33 thousands of elements and over 89 thousand nodes. It was built of 15-node solid elements, each containing 6 Gauss points. The analysis was carried out in two different finite element mashes. Initial calculations were conducted in a mesh on a circular plan, denser around the pile. The ultimate calculations were carried on a subsoil model in the axial–symmetrical system. Owing to this, it was possible to optimize the extent of the calculation problem. The assumed calculation area was on a rectangular plan with the longer sides parallel to the pile bending plane. The range of the subsoil displacement zones in front of the pile and width of the lateral zones of the subsoil interacting with the pile shaft were taken into account during the division of the calculation area. This area was referred to the diameter of pile (D). The following dimensions were assumed: in the plane of the load action - 12D, however, in the perpendicular direction - 8D. The bottom of the lump of the analytical piece of subsoil corresponded to a 15 m pit in the model scale. The geometric dimensions of the pile numerical model were like those of the pile subjected to empirical investigation. An analytical analysis was conducted for a single pile of 1.2 m in diameter, embedded to depths of 5 m in homogenous sand. The Mohr-Coulomb model of subsoil was used for the calculations. The calculation parameters for the sand were assumed based on the geotechnical field investigation at the site where tentative loading of the same pile as in the analytical analysis was carried out; internal friction angle $\varphi = 35^{O}$, modulus of deformation E=120 MPa, cohesion c = 0 MPa, Poisson's ratio = 0.3.

3.2. Analytical analysis assumptions

The numerical model was subjected to validation on account of adapting the piles, each 1.2 m in diameter, embedded in sand to depths of 5 m, to field investigation conditions. Figure 2 show field investigation conditions of hybrid pile. The computation results we referred to the deflection measurements for field investigated piles with and without a horizontal plate in subsoil in full-scale. The application of the FEM analytical analysis for the pile in the three-dimensional (3D) system made it possible to obtain much information about the processes occurring in the subsoil around the pile. This meant a possibility of verifying the hitherto applied, simplified methods of calculating bent piles.

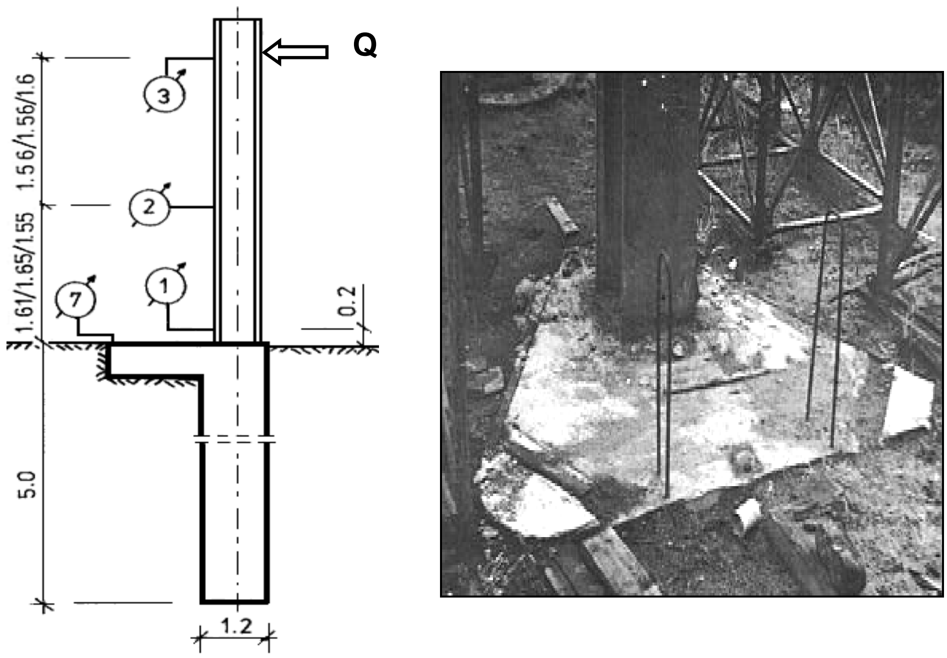

Fig. 2. Field investigation conditions of hybrid pile; a) model scheme, b). field investigation

Rys. 2. Warunki badania polowych pala hybrydowego; a) schemat modelu, b) badania polowe

3.3. 3D FEM calculations

A few series of calculations for single piles of 1.2 m in diameter, 5 m long - standard (without plate) and hybrid ones (with plate) were conducted [5]. The lateral load of the pile was concentrated force incrementing within the 0÷500 kN range. Load was applied to the pile at a height of 4m over the ground surface, as it was in the field investigation. The 3D FEM calculations allowed much wider understanding of the pile-subsoil interaction. In the range of compared load values applied in the field investigation and in a 3D FEM analysis the computed pile head displacements were basically in agreement with those measured. The lateral loads of piles assumed for the calculations enabled analyzing their behavior in the displacement range up to 120 mm and pile head rotation up to 1 rd. On account of the significant influence of the pile deflection non-linearity, the scope of the FEM analysis was reduced to 0÷60 mm pile head displacements in the applied soil analytical model. Figure 3 shows comparison of results obtained from the 3D FEM present analysis and full scale tests standard pile (without plate) Figure 4 shows subsoil deformation around 3D numerical models of piles; conventional and hybrid once. Figure 5 show comparison of subsoil deformations in the area of 5m long pile. The results presented are for successive stages causing pile head displacement: 10 mm, 20 mm and 40 mm.

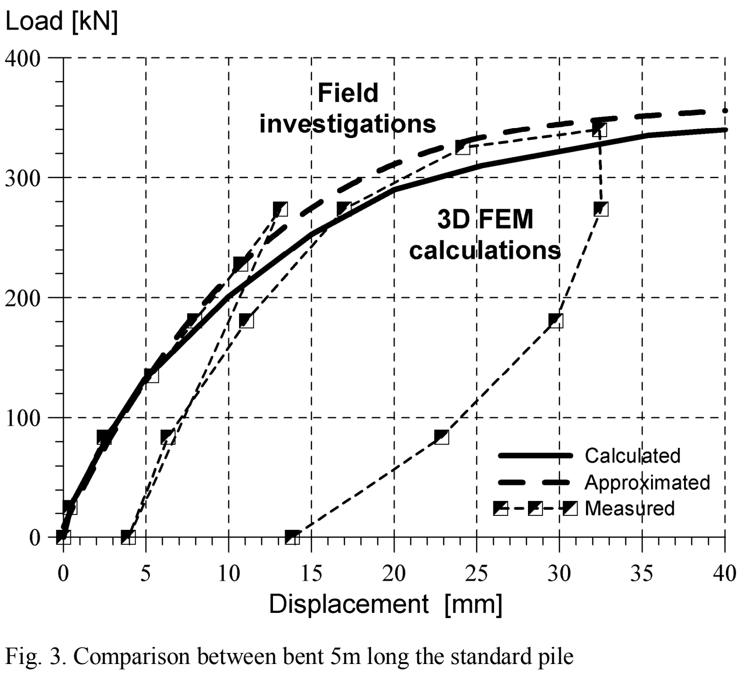

Fig. 3. Comparison between bent 5m long the standard pile

Rys. 3. Porównanie między wygięciami standardowych pali o długości 5 m

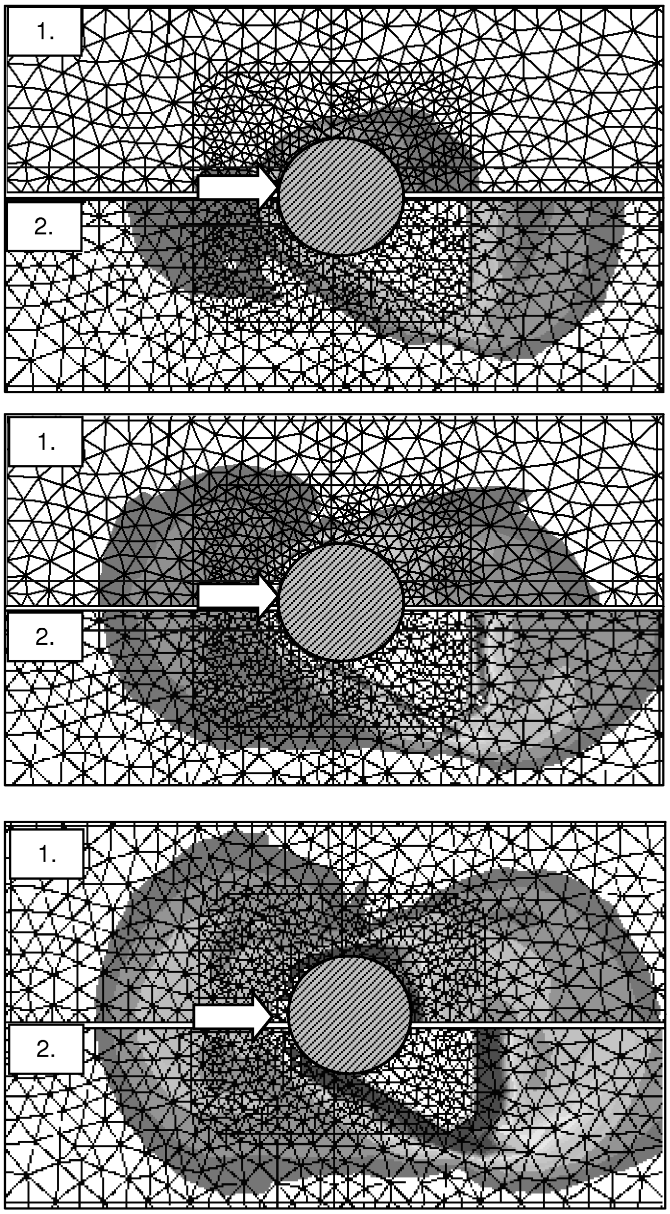

Fig. 4. Soil deformations at ground level around to 5 long pile model loaded with horizontal force and bending moment; 1 – standard pile, 2 - hybrid pile (with plate)

Rys. 4. Deformacje gruntu na poziomie gruntu wokół modelu pala o długości 5 m obciążonego siłą poziomą i momentem zginającym; 1 – pal standardowy, 2 – pal hybrydowy (z płytą)

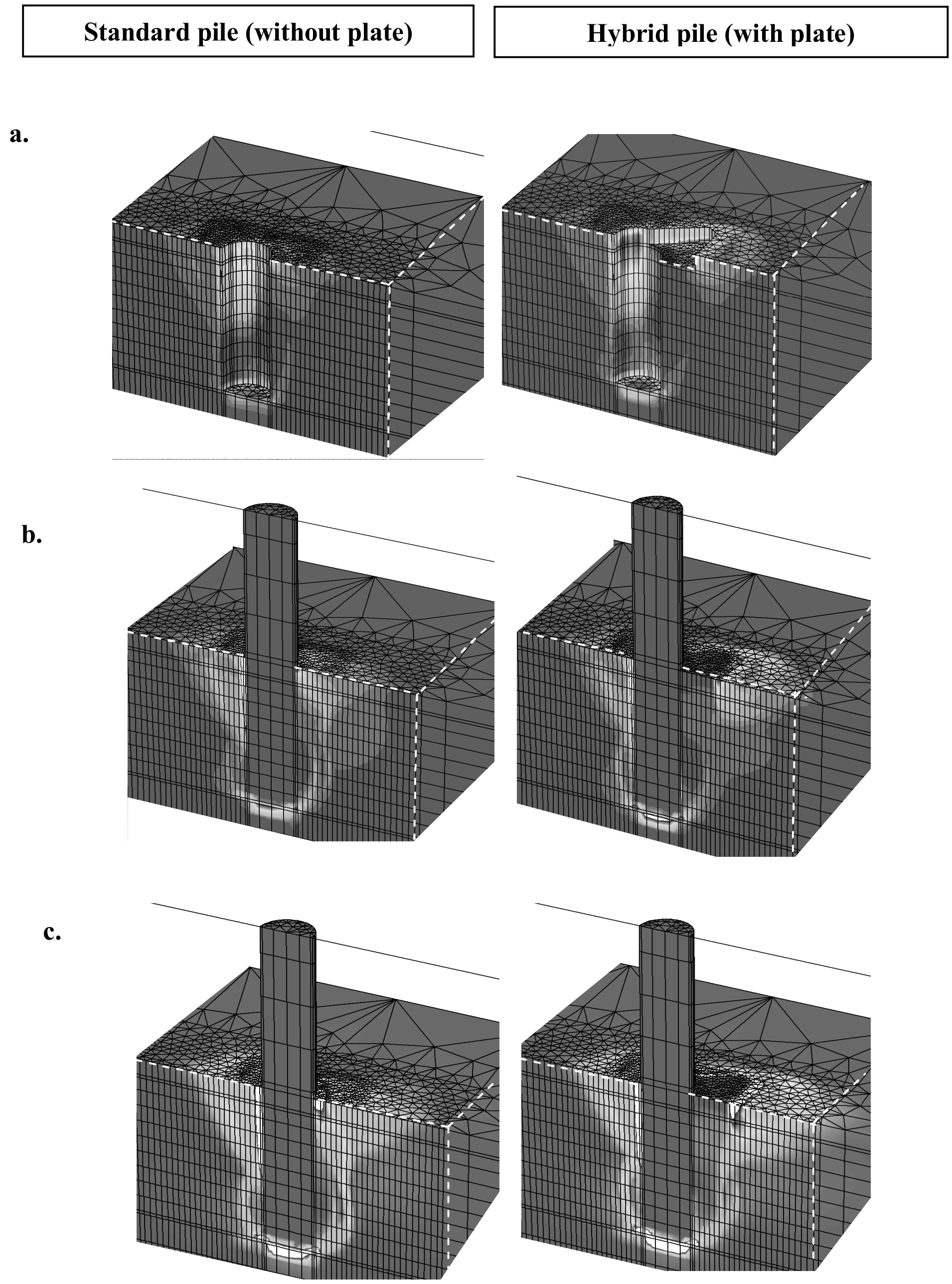

Fig. 5. Comparison of subsoil deformations in the area of 5 m long pile at its head displacements: a) 10 mm, b) 20 mm, c) 40 mm

Rys. 5. Porównanie deformacji warstw gruntu w pobliżu pala o długości 5 m przy przemieszczeniu jego głowicy: a) 10 mm, b) 20 mm, c) 40 mm

3.4. Results of soil-pile interaction analysis

The initial stage of pile bending with 0 - 500 kN horizontal force at pile head deflection less then of 60 mm was analyzed in detail. The results were presented graphically for depths of 0.6 m, 1 m, 1.5 m, 2 m and 3 m. The loading parameters used in the analysis were: horizontal deformation of the soil ε, horizontal stress in the ground σ and horizontal displacements of the pile head in the load plane y. The stress-strain dependence comparison presented in figure 6 indicate that for both a 5 m long pile it is possible to find the ultimate deformation capacity of soil at which it is pushed up. In both cases the value is ε = 0.3 % and occurs in the subsoil in front of the pile shaft at a depth of x = 0.6 m, i.e. just below the bottom of the plate. It corresponds to the values of the horizontal stress in ground σ, within 150 - 200 kPa. Such a state of stress in the ground occurred at horizontal force load Q = 300 kN for the 5m long pile. During a further increase in the lateral load applied to the pile there occurs an intensive deformation increment in the soil, which can be seen in the diagram as heaving or change in the slope of the curves describing the behavior of the soil around the pile without plate within the depth range of x = 0.6÷1.5 m. The attainment of the ultimate deformation capacity of soil around to the shaft pile is, in the case of the two piles, related to the displacement of their heads by y = 10 mm. This corresponds to Q = 300 kN for the 5m pile. Further increase in lateral load applied to a standard pile (without plate) brings about a significant non-linear increment in its deflection. A hybrid pile (with plate) stays elastic in subsoil within a much wider load range than a standard pile of the same diameter and length. This follows from initially (at y < 10 mm pile head displacement) small passive earth pressure occurring under the plate. Within the displacement range y = 10 ÷ 40 mm, occurring at θ = 0.2 ÷ 0.4 rd angle shaft rotation, horizontal components of the stress in the ground in front of a hybrid pile (with plate) grow more than those in front of a standard pile (without plate). At pile head deflections y above 40 mm, stress in the ground reaches the constant value which, in this analysis, was used as a measure of plate effect.

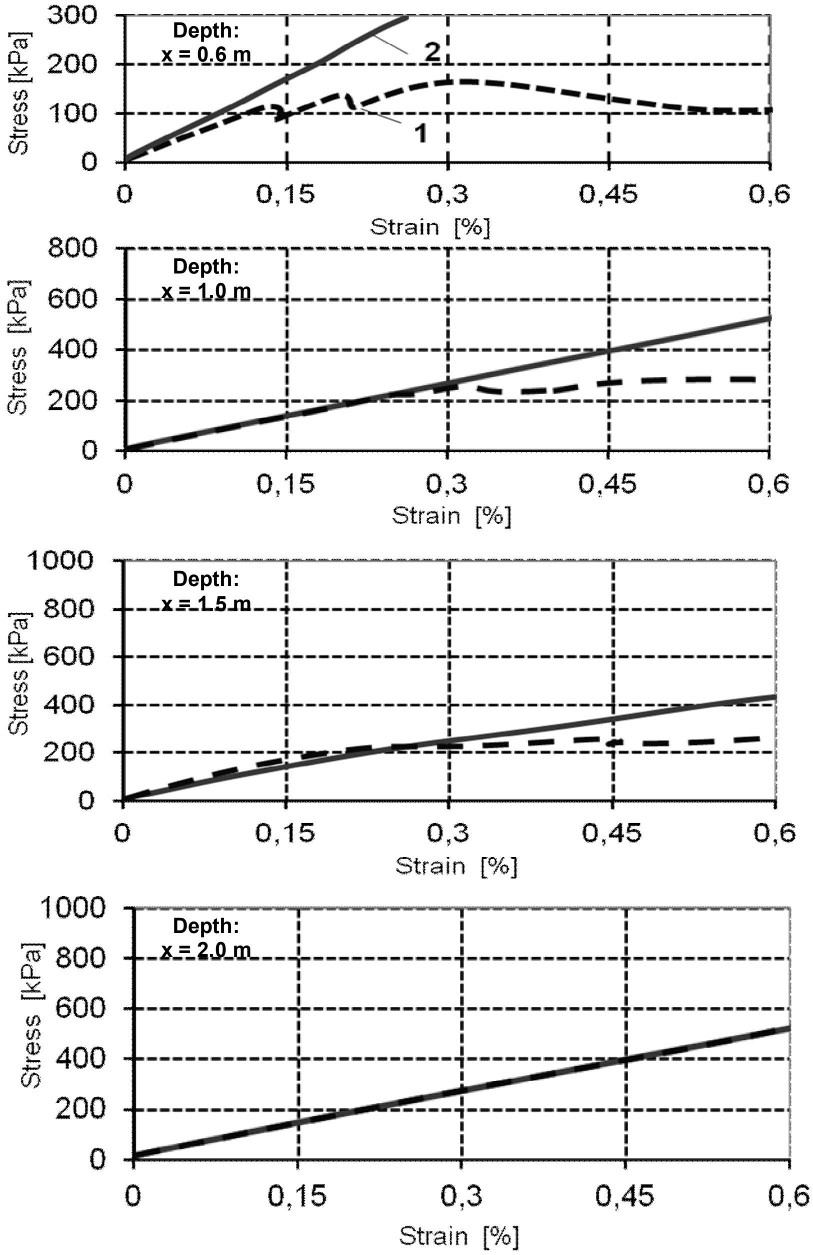

Fig. 6. Plots of stress-strain dependences at various depths in subsoil in front of pile, obtained based on 3D FEM calculations for 5 m long pile; 1- standard pile, 2 – hybrid pile

Rys. 6. Wykresy zależności naprężenie – odkształcenie na różnych głębokościach gruntu z przodu pala, określona w oparciu o trójwymiarowe obliczenia MES dla pala o długości 5 m; 1 – pal standardowy, 2 – pal hybrydowy

4. Evaluation of hybrid foundation stability

The value of coefficient Ep, described as a ratio of the standard pile head deflection to that of a hybrid pile head deflection under the same load, was assumed to be used as a measure of the plate effect. A parameter Ep defined that way characterizes the effect of the cantilever plate on the extent of the hybrid pile deflection. Based on the field investigation results, a comparative analysis of the deflections of hybrid piles (with plates) and standard ones (without plates), was conducted within the range of loads applied in particular investigation stages. The analysis ignored the response of the piles in the initial 0-60 kN load stage due to a wide scatter of the results due to the compaction of the soil under the plates of the two tested piles. Figure 7 present the plots of the dependence of coefficient Ep on the lateral load of 1.2 m diameter piles embedded 5 m in the sand. During the loading of the piles with cantilever plates and without them, the effectiveness of the plates was in the range of 1.3 - 1.7 . The values above 1.0 mean that the deflection of the pile with a plate was smaller than that without it. This indicates that in the case of a hybrid pile its deflection, compared to that of a standard one, decreased by 70% - 30% . The increase in lateral load was accompanied by a gradual increase in the effectiveness of the plates. In the range of small lateral loads applied, both hybrid and standard piles showed elastic response in the ground.

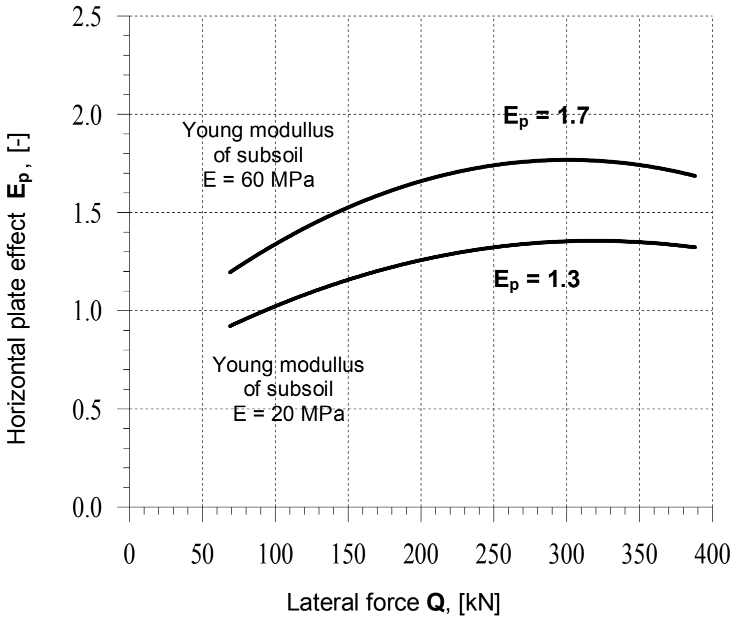

Fig. 7. Plate effect describing lateral stiffness increase of hybrid pile

Rys. 7. Efekt płyty opisujący wzrost sztywności giętej pala hybrydowego

The deflection measurements demonstrated that for 1.2 m diameter piles embedded in fine sand, the ultimate horizontal displacement of the standard pile head characterizing its elastic response in the soil was 5-7 mm. At a greater load, when the pile deflection at the ground surface was above 2 mm, the plate effect Ep values were bigger than 1.0. It means that the hybrid pile deflections were smaller compared to those of the standard pile without plate. Further load increase caused a nonlinear deflection growth of the 5 m long piles and a greater lateral pressure on the soil. When the hybrid piles were subjected to force load and bending moment, their deflections were by 30÷70 % smaller than those of the standard ones, depending on the plate subgrade deformability. In the case of the investigated 1.2 m diameter piles, the plate effect Ep rose gradually in the 0-300 kN range to stabilize under a load greater than 300 kN at 1.7 and 1.3 for 5m long piles. The activity differences between the plate effect of the two piles at their loading follow, from the different modulus of deformation of the sand layer 0.5 m thickness, which the plates were embedded (for Young modullus of subsoil E = 60 MPa, and E = 20 MPa).

5. Conclusion

This study refers to one of essential problems in designing retaining walls, bridge abutments and pillars for viaducts. Frequently the number of piles results from the need of assuring adequate lateral rigidity of support, rather then from required vertical load capacity. A rational design of a structure supported on hybrid piles necessitates a careful investigation of its stability and defining the real extent of displacements as the latter usually decide the serviceable conditions of the structure. It follows from the conducted research work and the author's theoretical analyses that finding the course of the hybrid foundation displacement changes is fairly complicated as the soil-foundation interaction below the cantilever plate area under spatial system condition has to be considered. Research into this issue is however, of vital importance for the assessment of the stability of single piles with a plate cap. It refers in particular to designing bridge stub abutment and embedded retaining walls loaded with considerable lateral forces. The effect of the presented field investigations and numerical analysis is:

- Awareness of a possibility of a new treatment of a pile cap while considering the soil-pile interaction under lateral load; the result is a new, complementary classification of foundations which distinguishes the *hybrid foundations* and is based in particular on considering their interaction with the ground in the in initial stage of the displacement increment.
- Setting out, based on the author's investigation, the reason for defining the *hybrid foundation* and describing its nature which consists in transmitting, in a specific way, lateral loads into the subsoil in the spatial soil-foundation interaction system.

- Establishing by numerical analysis 3D FEM the extent of an effective increase of the lateral stiffness of the pile to be bent by joining it to a horizontal plate rested on subsoil.

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INTERAKCJA GRUNT – PAL HYBRYDOWY PODDANY OBCIĄŻENIU BOCZNEMU

Streszczenie

Artykuł prezentuje problemy stateczności poziomo obciążonych pali w trójwymiarowym stanie obciążenia. Uzyskane wyniki opierają się na pracach uwzględniających oszacowanie interakcji pomiędzy gruntem i palem, jak również na podstawie analiz numerycznych w przestrzennym układzie interakcji pomiędzy gruntem a palem. Analizy numeryczne Autora dotyczące pali hybrydowych wykazały większą sztywność boczną spowodowaną korzystną współpracą gruntu i pala w określonym obszarze przemieszczeń spowodowanych obciążeniem bocznym. Bazując na palach osadzono gruntach niespoistych zostały rozpoznane zjawiska występujące w gruncie, oraz zostało przeprowadzone ilościowe oszacowanie przemieszczeń pali spowodowane siłą poziomą i momentem zginającym.

Słowa kluczowe: modelowanie numeryczne, pale, obciążenie boczne, interakcja grunt - fundament, trójwymiarowy model MES

Przesłano do redakcji:26.05.2015
Przyjęto do druku:10.01.2016

DOI: 10.7862/rb.2015.208