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NUMERIČKI MODEL GRUPE BUŠENIH ŠIPOVA OPTEREĆENE PROIZVOLJNIM HORIZONTALNIM OPTEREĆENJEM

Rezime:

Temelji vetroturbina, mostova, naftnih platformi, industrijskih dimnjaka, potpornih konstrukcija, pristaništa itd. mogu biti izloženi dejstvu značajnih horizontalnih opterećenja iz različitih izvora. Tačna procena nosivosti temelja ovih konstrukcija je neophodna, naročito u slučaju temelja na grupama šipova. Horizontalno opterećenje na grupu šipova može imati proizvoljan pravac. U ovom radu su prikazani neki bitni aspekti numeričkog modeliranja grupe bušenih šipova opterećene horizontalnim opterećenjem proizvoljnog pravca primenom MKE. Prikazani su i analizirani parametri modela, validacija modela i tehnike obrade rezultata. Puni 3D model je neophodan za tačno rešenje problema.

Ključne reči: grupa šipova, horizontalno opterećenje, PLAXIS 3D, Python, HS model

NUMERICAL MODEL OF BORED PILE GROUP UNDER ARBITRARY HORIZONTAL LOADING

Summary:

Foundations of wind turbines, bridges, offshore platforms, industrial chimneys, retaining structures, marine and harbor structures etc. can be loaded with significant horizontal loads from various sources. Appropriate assessment of the foundations capacity of these structures is necessary, especially when these structures are supported by pile groups. The horizontal loading on the pile group may have arbitrary direction. This paper addresses some important aspects of FEM numerical modeling of a bored pile group under arbitrary horizontal loading. Model parameters, validation and post-processing techniques are presented and discussed. The full 3D FEM model was found to be necessary for the correct problem solution.

Key words: pile group, horizontal loading, PLAXIS 3D, Python, HS model

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1. INTRODUCTION

Pile foundations are usually designed as closely spaced, square or rectangular pile groups. Beside their primary function to transfer the vertical loads, pile groups can be subjected to significant horizontal loads. These loads can originate from various sources: wave, current and ice action, ship/vehicle impacts, wind and earth pressure, earthquake, traffic acceleration, braking forces, soil displacements etc. The examples of horizontally loaded engineering structures are wind turbines, bridges, offshore platforms, industrial chimneys, retaining structures, marine and harbor structures etc. The magnitude of horizontal load is usually 10-15% of vertical load, and up to 30% in offshore structures [1]. Engineering problems that can arise due to the inappropriate assessment of the pile group response can be very serious. In the cases of bridges or other structures supported by pile foundations, only a few centimeters of lateral displacements can cause significant stress development [2].

When the pile group is loaded horizontally, stress-strain fields of adjacent piles overlap, followed with the separation ("gapping") between the piles and the soil behind the piles. The influence of the front pile row on lateral response of trailing (rear) pile rows is known as "shadowing". Due to soil-structure interaction effects, load-displacement behavior of a pile inside the group is different from the behavior of an equivalent single pile (Figure 1). When the pile spacing is increased, the interaction effects become less significant.

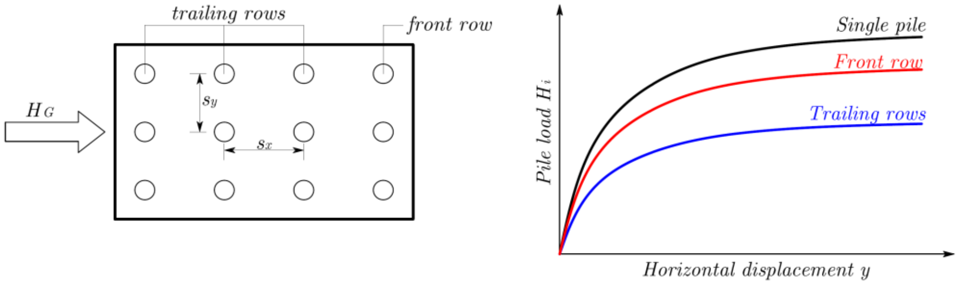

Figure 1 - Influence of the "shadowing" on the load distribution inside the pile group

The response of the pile group under horizontal loading has been intensively investigated. Full-scale and small scale experiments can eliminate the most of the uncertainties of the considered problem. The conducted experimental studies of the horizontally loaded pile groups are summarized in several papers [3-5]. However, high costs of such experiments motivate the use of numerical modeling as the faster and cheaper alternative, especially for large scope studies. Many numerical solutions with different level of complexity have been proposed: closed form and empirical solutions [6-8], limit equilibrium methods [9-10], Strain Wedge method [11-13] and p-y curve method [14-16]. The fast development of computers led to use of continuum-based methods, which allow for the full discretization of both soil and the structure, combined with the advanced soil constitutive models. Continuum-based approach can provide a more realistic analysis, with the use of material model parameters with a clear physical meaning. On the contrary, continuum-based methods require more effort for the model preparation, as well as the higher computer hardware requirements.

So far, the most of the studies on pile groups under horizontal loading have considered loading along one of the two orthogonal directions, parallel to the edge of pile group. However, due to the stochastic nature of its source, the horizontal loading on the pile group may have arbitrary direction. The number of studies dealing with the pile groups under arbitrary loading is limited [17-22], and they emphasize that the loading direction has great influence on the response of the pile group. This paper therefore addresses some important aspects of numerical modeling of a long bored pile group under arbitrary horizontal loading. First the important problem parameters and modeling approaches are summarized. Then the numerical model, along with post-processing procedures is presented and the main conclusions are derived.

2. MAIN PROBLEM PARAMETERS

Interaction inside the pile group (PG) is influenced by various factors, such as: pile spacing and arrangement inside the pile group, total number of piles, pile stiffness, length and diameter, pile installation method, soil conditions, loading level, pile head conditions, pile-soil slippage and separation and presence of axial loading. "Apriori" sensitivity analysis of different problem parameters via broad literature survey was done in [23], with the following conclusions:

- the problem of horizontally loaded pile group is a 3D engineering problem, especially in the case of arbitrary loading direction;
- pile spacing and configuration are identified as the main factors for the PG interaction;
- pile-soil slippage/separation effects must be considered in order to assess PG response;
- soil profile, in general, can be modeled as homogeneous, because only the top soil layer properties significantly influence the long pile group response;
- for the working load conditions, linear elastic pile behavior can be assumed;
- influence of the axial loading can be neglected in numerical model;
- pile length and diameter are identified as the less important problem parameters.

According to Mokwa and Duncan [24], boundary conditions at the pile head are somewhere in between fixed and free head pile. Same authors pointed out that the pure fixed head conditions are hard to achieve in reality, even when the pile cap is very stiff. In this paper, therefore, only free head bored piles were considered.

3. NUMERICAL MODEL

Nowadays, the Finite Element Method (FEM) is considered as the most reliable and widely used numerical method for engineering analysis of complex foundation systems. FEM allows for detailed modeling of all important pile foundation model components: pile geometry, soil continuity and nonlinear behavior, and especially the pile-soil interaction through the slippage and gapping. EC 7 [25] suggests the use of soil-structure interaction in the numerical analysis, especially in the case of complex foundations, such as laterally loaded pile foundations.

Within this paper, the numerical model of the bored PG under arbitrary horizontal loading was designed and validated using FEM code PLAXIS 3D (Anniversary Edition) [26]. It is a world-wide used code for the stress-strain, stability and groundwater flow analysis in geotechnical engineering, that supports an easy input of the models with complex geometry, as well as the illustrative presentation of the results. It also features various constitutive models.

Two pile modeling techniques are mainly used in PLAXIS 3D: full 3D (solid) pile model, and recently implemented embedded beam model.

3.1. FULL 3D MODEL VS. EMBEDDED BEAM MODEL

In full 3D analysis, piles are discretized using 3D (solid) finite elements. The advantage of such modeling is the fact that the pile shaft geometry and soil-structure interaction along it are modeled accurately. However, this usually leads to very large models, by means of computational complexity, which can be time consuming in everyday engineering practice.

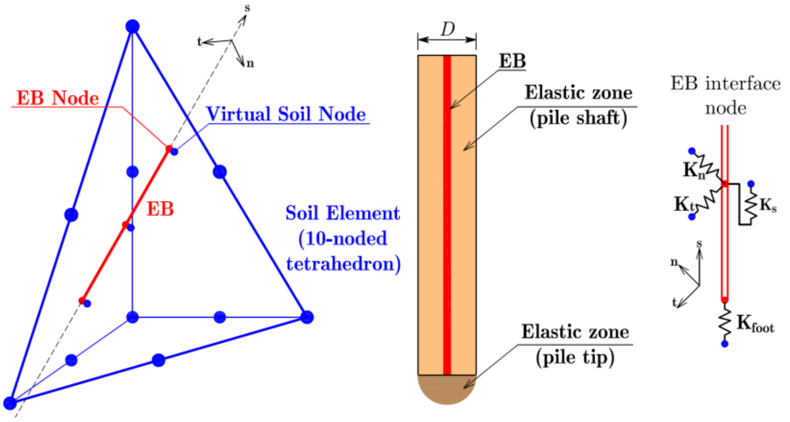

Figure 2 - Embedded beam model in PLAXIS 3D (after Brinkgreve et al. [26]).

The embedded beam model was introduced by Sadek and Shahrour [27]. In this modeling approach, pile isn't discretized using 3D elements, but replaced with advanced formulation. Embedded beam is a beam element that can be inserted (embedded) at arbitrary direction into the existing FE mesh of 3D (solid) elements. Upon insertion, additional "virtual" nodes are generated at penetration points. Therefore, embedded beam elements do not affect the existing FE mesh discretization of soil continuum. As an improvement of initial formulation [27], an elastic zone is assumed around the embedded beam element [26], where plasticity in soil elements cannot occur. This elastic zone simulates the space occupied by real pile (Figure 2). Pile-soil interaction is modeled using special interface, 3-node spring elements in axial and lateral directions. These interface elements "connect" the embedded beam nodes with the virtual soil nodes. The main advantage of embedded beam model is increased calculation speed and easy determination of section forces along the pile. However, because no real discretization of pile volume is made, embedded beam doesn't take into account the sliding between the pile and the surrounding soil. The soil-structure interaction is modeled along the pile axis, instead the pile shaft, so the gapping between the soil and the pile cannot be accurately modeled.

Comparison of these two modeling techniques (EB-embedded beam, VP-full 3D volume pile model) was studied by Marjanović et al. [28] on idealized example of 2x2 pile group in loose and dense sand (Figures 3, 4). Numerical simulations were performed as displacement control tests with prescribed displacements of 0.2D at pile tops. The case of fully rigid (R_{inter}=1) and soft pile-soil interface (R_{inter}=0.5) were discussed. The R_{inter} is the non-dimensional strength reduction factor (< 1.0) that reduces the shear strength parameters (c' and φ') of the Mohr Coulomb (MC) model to values c_{inter}, φ_{inter} at pile-soil interface.

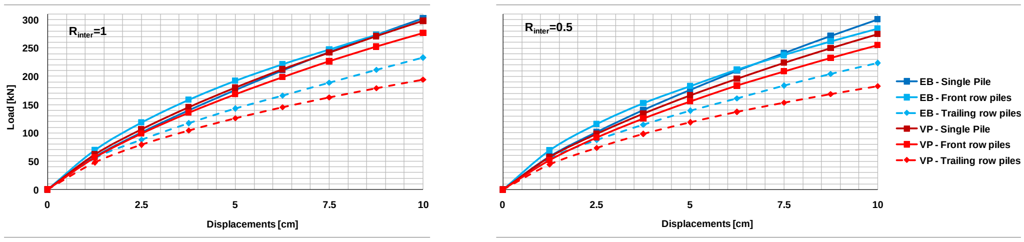

Figure 3 - Load-displacement curves of single pile and group piles in dense sand

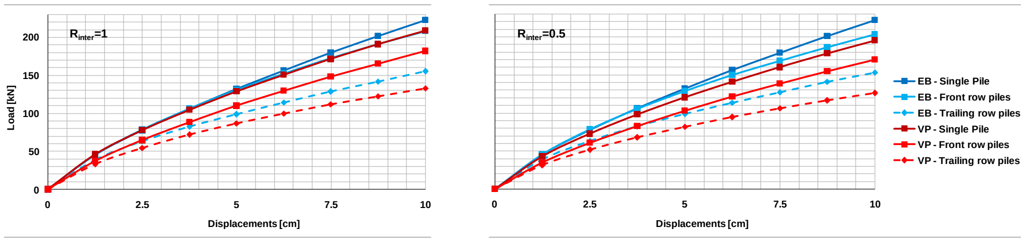

Figure 4 - Load-displacement curves of single pile and group piles in loose sand

The difference in bearing capacity between front and trailing rows was observed for both EB and VP models. This means that the both models can qualitatively resemble the horizontally loaded pile group behavior (Figure 1). The results also show that the interface properties don't influence the load-displacement response of EB models, while the VP models are influenced, as expected. This is associated with the formulation of embedded beam interface, where only shear stresses in axial direction are governed by interface input parameters. Due to (current) limitations of the PLAXIS 3D embedded beam model for lateral loading, the full 3D pile group model is recommended. However, recent researches [29-31] by several authors show promising improvements of current embedded beam model formulation.

3.2. PROPOSED MODEL DESCRIPTION

Based on the aforementioned comparison of two modeling techniques, full 3D pile group model is proposed. The application of model symmetry is not possible.

The pile constitutive behavior is modeled using the linear elastic model, based on the generalized Hooke's law. The spacing between the pile tip and the bottom model boundary was chosen to be relatively small, because the lateral pile group response is mainly governed by the active pile length.

The pile-soil contact is modeled using thin 2D interface elements. These elements are different from the regular finite elements - they have pairs of nodes instead of single nodes, with the distance between the two nodes of a node pair equal to zero. Each node has three translational degrees of freedom (u_x, u_y, u_z). As the result, these elements allow for differential displacements between the node pairs to simulate both slipping and gapping on the pile-soil contact [26]. The constitutive behavior of pile-soil interface is defined by the elastic-perfectly plastic Mohr-Coulomb model with a non-associated flow rule and zero tension cut-off criterion (when tension develops, a gap between the pile and the surrounding soil is generated). In general, there is the lack of the experimental data for real pile-soil interface parameters. Suitable values of R_{inter} are recommended in the literature [26] for different soil types, and usual value is around 0.5.

The extraction of the section forces from volume elements is implemented in PLAXIS 3D, but this step cannot be done automatically. In order to simplify the calculation of pile section forces, the "dummy" beams are added into the numerical model (Figure 5). The elastic beam finite elements with very small bending stiffness (10^6 times smaller than the pile bending stiffness *EI*) are inserted along the pile axes. Because the "dummy" beam stiffness is very small, model stiffness matrix remains unchanged. "Dummy" beams are enforced to deform together with the piles, and the section forces are then easily computed by multiplication of "dummy" beam section forces with 10^6. Such modeling concept is common when the laterally loaded piles are modeled using the 3D elements [32-33].

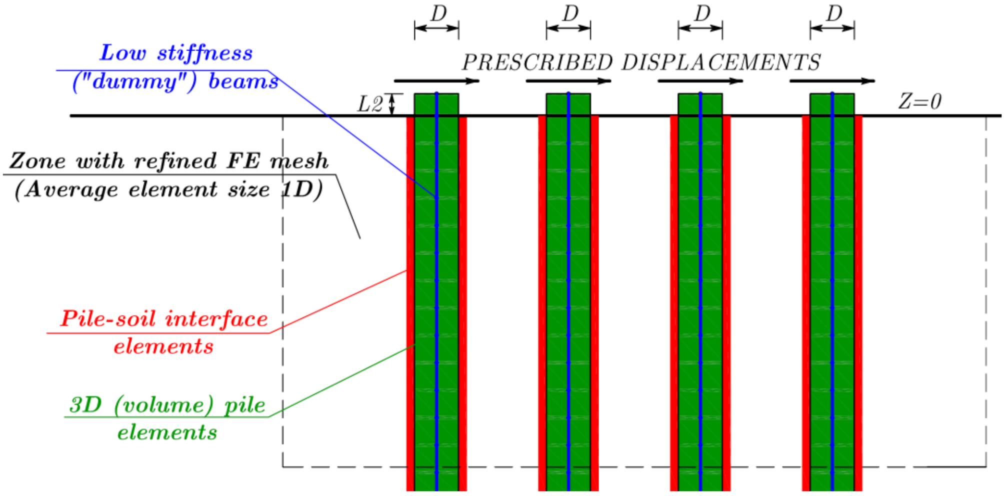

Figure 5 - Numerical model components

Soil constitutive behavior is modeled using the Hardening Soil (HS) model [34]. As in the case of the MC model, the limit stress states of the HS model are defined using the parameters for the MC failure criterion (cohesion c', angle of internal friction φ' and dilation angle ψ). However, the soil stiffness is described more accurately, using advanced stiffness parameters: the triaxial loading stiffness E_{50}, the triaxial unloading stiffness E_{ur} and the oedometer loading stiffness E_{oed}. These stiffnesses are not constants, but are dependent on the loading level (principal stress state). The magnitude of the stress level dependency is governed using the parameter m. Opposite to MC model, the yield surface of the HS model is not fixed in the principal stress space, but it can expand due to plastic straining. Two types of hardening are included in the model: shear hardening (due to primary deviatoric loading) and compression hardening (due to oedometer and isotropic loading).

3.3. CALCULATION STAGES AND RESULTS POST-PROCESSING

Proposed numerical model is calculated as the staged (phase) model, and consists of the following stages:

- Initial (K_0) stage, where the initial (geostatic) stress field in the soil is established;
- Construction stage - soil volumes at pile positions are replaced with pile volumes (wished-in place concept). 2D interface elements are also activated in this stage. Because this study considers only the bored piles, installation effects can be neglected;
- Prescribed displacements - application of prescribed displacements at the pile top, in desired loading direction. The prescribed displacements simulate the displacement control test under static loading conditions

PLAXIS 3D allows the extraction of all results in Euclidean XY space. However, for the arbitrary loading case, the resultant maximum displacement, shear forces and bending moments must be recalculated, using simple vector algebra (Figure 6):

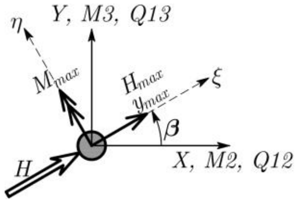

Figure 6 - Directions of the maximum displacements, shear forces, and bending moments

The shear forces extracted directly from the "dummy" beams in PLAXIS 3D are slightly unrealistic, which is the issue recognized and analyzed by Tedesco [32], who concluded that such behavior could be associated with the PLAXIS 3D beam elements, that compute the shear forces using the bending moment derivative along the pile length. In order to properly evaluate the pile shear forces, first the pile bending moments are approximated using the B-spline approximations, with 10 interior knots and 5th order spline interpolation. Then the shear forces profile was computed by differentiation of the fitted pile bending moments line along the pile.

3.4. MODEL VALIDATION

Numerical model was validated by the back-calculation of the small-scale centrifuge pile group test by Kotthaus [35]. Trial and error analysis was used to match the experimental results with the model response. Both single pile and the three pile row at 3D spacing were back-calculated [23]. Despite slight discrepancies, results of the model validation show satisfactory match with the experimental results and the overall performance of the numerical model is considered to be acceptably accurate.

4. CONCLUSIONS

FEM numerical model of the long bored pile group was designed and validated by back calculation of the existing experimental results from the literature. Important aspects of the numerical modeling of pile group under arbitrary horizontal loading were emphasized. Based on the presented analysis, the following conclusions can be made:

- Modeling of the pile group under horizontal loading using the proposed full 3D FEM model provide the acceptable results for the case of bored piles
- Embedded beam model implemented in PLAXIS 3D is not adequate for precise numerical modeling of horizontally loaded pile group

Presented results also provide several topics for future research in the field of numerical modeling. Alternative pile modeling approaches, such as improved embedded beam model formulation (with advanced interface), as well as the more advanced Strain Wedge model (with arbitrary wedge orientation), could lead to improvements of the speed of numerical simulations.

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