ON BEHAVIOUR OF LATERALLY LOADED FIXED HEAD PILE GROUP IN P-Y SOFT CLAY BELOW THE WATER TABLE SUBJECTED TO CYCLIC LOADING – SENSITIVITY ANALYSIS

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ABSTRACT
The paper presents the analysis of maximum generalized deflection of a laterally loaded pile group from a sensitivity theory standpoint. The soil in which the pile group is located is described by means of the p-y model (Matlock, 1970). The physical parameters of the p-y model and the bending stiffness of the member-piles are taken as the design variables. They are distributed along the length of the pile. Theoretical formulation of the sensitivity analysis of a laterally loaded pile group is described in reference to a single isolated pile. It is extended to a pile group in which each member-pile is considered as a pile-soil-pile system. The final product of the theoretical formulation is given in the form of sensitivity operators that describe how the spatial changes of the design variables affect the performance of the pile-soil-pile system. The results of the numerical investigations are presented and discussed.

RÉSUMÉ
Cet article présente une analyse de déflexion maximum généralisée d'un groupe de pilots chargé latéralement selon une théorie d'instablilité. Le sol dans lequel les pilots y sont ancrés est décrit en moyen du modèle p-y (Matlock, 1970). Les parametres physiques du modèle p-y est la rigidité de pilots-membres qui servent comme variables du plan. Ils sont distribués le long du pilot. La formulation théorique de l'analyse avec la base de théorie d'instabilité du groupe de pilots chargé latéralement fait reference à un seul pilot isolé. Il s'ajoute au groupe de pilots dans lequel chaque membre est considéré comme un système pilot-sol-pilot. Le produit final de la formulation théorique est donné sous forme d'opérateurs d'instabilité qui décrivent comment les changements spatiaux des variables du plan affectent la performance du système pilot-sol-pilot. Les resultats de nos investigations numériques sont présentés et discutés.

1. INTRODUCTION

The deep foundation supporting systems belong to those geotechnical engineering systems that are of key importance for human activities. They provide a support for such civil engineering systems as bridges, retaining walls, high rise buildings, offshore energy production systems, etc. The deep foundation systems arranged in pile groups, not only support axial load, but also resist to substantial lateral load.

The soil models developed in 70s of the twentieth century to support lateral load of deep foundation systems are known as p-y models, where p stands for soil reaction and y means a lateral deflection. These models are highly nonlinear and involve to their descriptions various soil strength parameters such as a cohesion c, a soil's unit weight γ, a width b of the pile where the soil reaction p can develop, etc. The p-y soil models serve basically for the determination of kinematic and strength performances of laterally loaded pile-soil systems. The standard analysis of p-y pile system considers all strength parameters being assigned spatially to the system in permanent fashion.

The sensitivity theory considers the material properties (in general terms) as spatial functions. This means that sensitivity theory postulates that the changes in the performance of the system when subjected to constant (unchangeable) load are attributed to the changes of material parameters of the system. It is apparent that there are some spatially localized areas where the changes of the material parameters have more pronounced effects on the changes of the performance of the system than in the others. The knowledge about it when implemented at the design stage of a foundation system makes the design system more economical. For already existing systems the sensitivity theory has also useful remedy for improvement of their performance in the course of life-service deteriorations. The recommendations on the improvement, rehabilitation or renovation of ageing systems made based on the sensitivity analysis are in tune with sustainable development strategy.

The spatial functions determined in the scope of sensitivity analysis that allows assessing and localizing those parameters that affect the performance of the system are called the sensitivity operators. Physically, they represent the potential values of material parameter changes that contribute to the changes of the performance of the system.

In the paper the laterally loaded pile group embedded in p-y soft clay located below the water table subjected to cyclic loading (Matlock, 1970) is exposed to investigation from the standpoint of sensitivity theory of distributed parameters. The cyclicity of the loading is included into considerations in an implicit fashion. The assessment of sensitivity performance of a pile group means that each member-pile of the system is examined in the framework of sensitivity analysis. The brief outline of the theoretical formulation describes the notion of the adjoint system method used for investigations of member-piles of the pile group. The numerical investigations are conducted for discrete values of force Pg applied to the pile group cap. The member-piles are connected with cap in fixed fashion. The determined sensitivity operators that affect the changes of maximum deflection caused by the changes of the material parameters of pile-soil-pile system are presented in the diagramatic form.

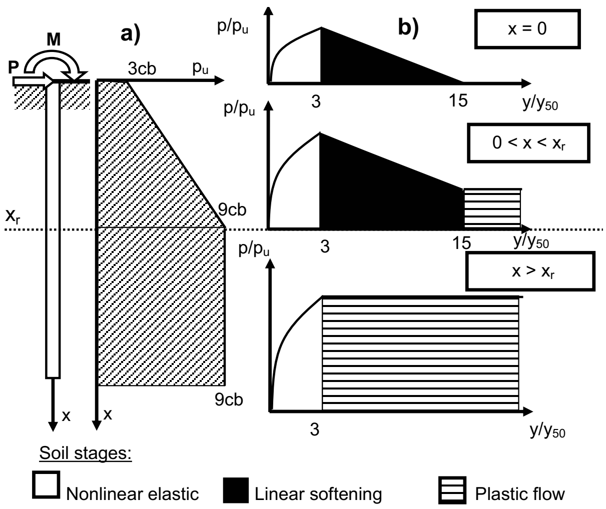


Figure 1. Constitutive p-y curve of soft clay located below the water table subjected to cyclic loading (after Matlock, 1970.)

2. THE BEHAVIOUR OF A PILE-SOIL AND PILE-SOIL-PILE SYSTEM EMBEDDED IN SOFT CLAY BELOW THE WATER TABLE SUBJECTED TO LATERAL CYCLIC LOADING

The single isolated piles and pile groups when subjected to lateral loading are commonly analyzed with assistance of a p-y soil model. They have been developed specifically for the type of interaction generated in these situations between the pile structure and the surrounding soil.

The reasons of broad popularity of p-y soil models used for design purposes in a variety of civil engineering structures are the following: they are based on the field studies; they enjoy high reliability; and they are implemented in the computer programs available for engineers.

Usually, the p-y models are graphically represented by the nonlinear springs. They are spatially continuous (with respect to the depth x) and mechanically discrete. The later characteristic means that any deformation (lateral displacement y) of a soil at arbitrary depth x has local character and is not transferred to any closest neighbouring point. However, when p-y soil model is used to provide the support to the laterally loaded pile, then the fact of application of a load to the pile structure generates the continuous deflection y of the pile structure which results in continuous deflection of the p-y soil.

Matlock's (1970) p-y model of soft clay below the water table subjected to cyclic loading that is employed in the investigations requires the involvement of the following physical quantities: the ultimate soil resistance p_u, the ε_{50} which stands for the strain corresponding to 50% of the maximum principal strain difference, the cohesion c, the submerged unit weight γ' and the width of a pile b where the soil reaction p can develop. The graphical representation of the p–y soil behaviour for soft clay below the water table subjected to cyclic loading is shown in Fig. 1.

It is presented in non-dimensional coordinate system. The vertical axis indicates the ratio (p/p_u) whereas the horizontal axis designates the ratio of an arbitrary lateral displacement y to the displacement $y_{50}=2.5b\varepsilon_{50}$. The ultimate soil resistance p_u is equal to 3cb at the soil surface and then increases linearly up to the depth of the reduced resistance x_r reaching the value p_u=9cb, and it remains constant thereafter. The depth x_r is determined from the continuity of the p_u that results in:

$$x_r = \frac{6cb}{\gamma' b + Jc} \qquad [1]$$

where J is the model constant that is recommended to be taken as 0.5.

Figure 1b shows that for the depth $x \leq x_r$ the p-y soil behaviour can be divided into three stages, which are: the non-linear elastic stage for the lateral deflection $y \leq y_{50}$, the linear softening stage for lateral displacement $3y_{50} \leq y \leq 15y_{50}$ and the plastic flow stage for the lateral displacement $y \geq 15y_{50}$. For the depth $x \geq x_r$ the behaviour of soft clay below the water table subjected to cyclic load is described by two stages, which are: the non-linear elastic stage for $y \leq y_{50}$, and the plastic flow stage for $y \geq 3y_{50}$.

The p-y soil models have been developed to provide an interaction between pile-soil system when subjected to lateral loading. However, the straightforward application of p-y model to laterally loaded pile group resulted in unsatisfactory results. This means that field results in terms of quantitative performance of the system demonstrated considerable difference when confronted with suitable numerical outcomes. The reason of this discord is caused by the development of a different interaction system that the pile-soil generates when being an isolated pile or a part of a pile group. In former case, it is considered as a pile-soil system whereas in latter scenario it creates a pile-soil-pile system. The identified interaction mechanisms show that when two identical pile-soil and pile-soil-pile system are subjected to the same load, they generate different deflections, such as the former being smaller than latter. The behaviour of a member-pile within a pile group is affected by the spacing s of the member piles as well as the spatial location (in geometrical sense) within the pile group.

The adaptation of the p-y models developed for single isolated pile-soil system to the pile group analysis is conducted by introducing the suitable f_m factors that are smaller than 1 ($f_m < 1$). They take into account the spacing s between the member-piles as well as geometrical location of a member-pile (e.g. differentiation leading row from first trailing row, second trailing row, etc).

The physical meaning of the f_m multipliers is to design a new, suitable p-y curve that has an envelope of soil reaction p compressed in comparison to the original soil reaction p envelope of a single isolated pile-soil system. Consequently, this means that the plastic flow of the soil adjacent to a member-pile of a pile-group is initiated by the smaller value of soil reaction p than in the case of single isolated pile-soil system. The f_m multipliers have been proposed by a number of researchers (e.g. Brown et al. 1988). Recently, Mokwa and Duncan (2001) reviewed over 350 research papers on this subject. Their review resulted in comprehensive recommendations of suitable f_m multipliers that are used in the presented research. Accordingly, the member-pile is considered to be treated as a single isolated pile-soil system when the spacing between the piles in the collection of the piles is equal to 6.

3. THEORETICAL FORMULATION OF SENSITIVITY ANALYSIS OF LATERALLY LOADED PILES AND PILE GROUPS

The performance of a structure or a system (e.g. pile-soil interaction system) is considered good if it performs as developed and provides an acceptable level of service over its intended life. The development of a good performance model depends on the condition and assessment methods, applied loads, material behaviour predictions, and taking into account climatic and environmental conditions.

It is important to identify key factors in addition to usage that affect the performance of the system in service as well as in the course of the life-service. The deterioration of the structure during in-service operations can be manifested by excessive deformation or various distortions. It is important to address such analysis in terms of structural model used in the design process with involvement of the possible changes of material properties of the system. These criteria can be suitably introduced through the distributed parameter sensitivity theory.

The detail theoretical formulation of sensitivity analysis of laterally loaded free-head long piles embedded in p-y soft clay below the water table subjected to cyclic loading is presented in Budkowska and Priyanto (2003a and 2003b). In this paper the sensitivity theory of distributed parameter is briefly outlined in reference to a single isolated pile. The objective of this section is to describe the specific features of sensitivity analysis developed for sensitivity investigations of pile groups when embedded in p-y soil model and subjected to lateral load.

The virtual work principle allows determining a generalized displacement of an arbitrary point of a system subjected to a given load. The investigated structure that is loaded is called the primary structure. The virtual generalized load $\bar{1}$ is applied to the temporary structure being in the state of deformation of the primary structure, which is called the adjoint structure. Based on the virtual work principle, the changes of maximum generalized displacement $\delta\mathbf{D}$ of a pile-soil system caused by the changes of the design variables vector $\delta\mathbf{z}$ are determined according to the following equation:

$$\bar{1}\delta\mathbf{D} = -\int_0^l \bar{M}\delta y''dx + \int_0^l \bar{p}\delta y dx \qquad [2]$$

where $\bar{1}$ stands for generalized virtual unit load applied to the adjoint pile-soil system,
$\bar{M}$, $\bar{p}$ are the internal forces of the adjoint structure resulting from the application of unit load $\bar{1}$,
δy, $\delta y''$ denote the variations of the generalized deflection lines imposed on the primary structure caused by the changes of the design variables vector $\delta\mathbf{z}$.

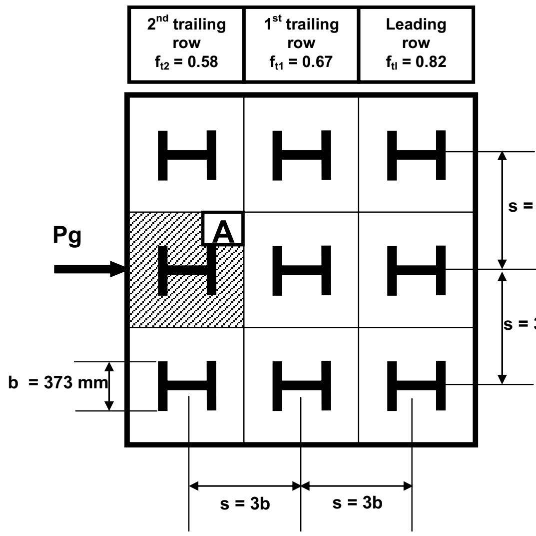


Figure 2. Pile group geometric characteristics employed in the sensitivity analysis.

The final form of sensitivity of $\delta\mathbf{D}$ due to the changes of $\delta\mathbf{z}$ that can be obtained from Eq. 2 requires performing a set of steps and satisfying some conditions. They are specified below:

• the determination of the unknown variations δy and $\delta y''$ of Eq. 2 calls for the reference to physical relationships written in variational form for p-y soil and pile structure,
• taking into account the condition that variations δy and $\delta y''$ are imposed on the primary structure that is subjected to unchangeable load and being in the state of static equilibrium,
• consequently, the imposed variations δy and $\delta y''$ do not produce any increment of internal forces in the primary system,
• the variations of the design variables $\delta\mathbf{z}$ are normalized with respect to their initial values $\mathbf{z}$,
• the process of normalization of $\delta\mathbf{z}$ with respect to $\mathbf{z}$ allows obtaining the sensitivity integrands expressed in terms of the same units.

Thus, the determination of the changes of the maximum generalized deflection $\delta\mathbf{D}$ caused by the changes of the normalized design variables vector $\delta\mathbf{z}_n$ (having components: $\delta(EI)_n$, δc_n, $\delta\gamma'_n$, $\delta\varepsilon_{50n}$, and δb_n) when the pile-soil interaction system is subjected to a constant value load is established by the following equation:

$$\bar{1}\delta\mathbf{D} = \int_0^l C_{EI}\delta(EI)_n dx + \int_0^l C_c \delta c_n dx + \int_0^l C_{\gamma'}\delta\gamma'_n dx + \int_0^l C_{\varepsilon_{50}}\delta\varepsilon_{50n} dx + \int_0^l C_b \delta b_n dx \quad [3]$$

where C_{EI}, C_c, $C_{\gamma'}$, $C_{\varepsilon 50}$ and C_b are the sensitivity operators affecting the maximum $\delta\mathbf{D}$ due to the changes of $\delta(EI)_n$, δc_n, $\delta\gamma'_n$, $\delta\varepsilon_{50n}$, and δb_n, respectively.

The sensitivity operators $C_{(...)}$ are also called the sensitivity integrands which are dependent on the depth x. Equation 3 is formulated for a single isolated pile-soil system. In case when a pile group is subjected to sensitivity investigation, an equation similar to Eq. 3 is required to be determined for each member-pile. The virtual work principle clearly sets the rules for type of virtual load that should be used.

Consequently, the adjoint pile group that contains a member-pile subjected to sensitivity analysis is loaded by the virtual force $\bar{P}g$ applied to the pile group cap that is determined in such a way that the portion of $\bar{P}g$ equal to $\bar{1}$ is applied to the member-pile of interest. The determination of $\bar{P}g$ employs the solution of the primary pile group system which is subjected to load Pg applied to the pile group cap. It is postulated that the same proportionality law is developed in distribution of the external force Pg to the member-piles of the primary pile group and $\bar{P}g$ when applied to the adjoint pile group system. It is worth noting that described approach of determination of $\bar{P}g$ for the member-pile of the adjoint pile group designated for sensitivity investigations is conducted in accordance with a rule-one at a time.

The integration of Eq. 3 with respect to spatial variable x (leaving the estimation of the design variables variations $\delta\mathbf{z}$ to the decision of an engineer) enables one to assess that portion of sensitivity of maximum generalized displacement $\delta\mathbf{D}$, which is associated with each change of the design variables. In mathematical terms, it is expressed as:

$$\bar{1}\delta\mathbf{D} = \left(A_{EI}\delta(EI)_n + A_c\delta c_n + A_{\gamma'}\delta\gamma'_n + A_{\varepsilon 50}\delta\varepsilon_{50n} + A_b\delta b_n\right) \quad [4]$$

where A_{EI}, A_c, $A_{\gamma'}$, $A_{\varepsilon 50}$, and A_b are the sensitivities of maximum generalized deflection $\delta\mathbf{D}$ due to the changes of normalized variations of the design variables $\delta(EI)_n$, δc_n, $\delta\gamma'_n$, $\delta\varepsilon_{50n}$, and δb_n, respectively.

Equation 4 forms basis for determination of sensitivity factors $F_{(...)}$ that define the contributions (expressed in %) that each of the design variables has on the change of the maximum generalized deflection $\delta\mathbf{D}$ when the pile group system is subjected to constant value of load. The sensitivity factors $F_{(...)}$ allow to classify quantitatively the order of importance the changes of the design variables have on the changes of the performance of the system. In numerical terms, the described method is formulated as:

$$A_{tot} = (A_{EI} + A_c + A_{\gamma'} + A_{\varepsilon 50} + A_b) \quad [5]$$

Combining Eq. 5 with Eq. 4 results in reshaping of Eq. 4 to the following form:

$$\begin{aligned}\bar{1}\delta\mathbf{D} &= (A_{tot})\begin{pmatrix}\frac{A_{EI}}{A_{tot}}\delta(EI)_n + \frac{A_c}{A_{tot}}\delta c_n + \frac{A_{\gamma'}}{A_{tot}}\delta\gamma'_n \\ + \frac{A_{\varepsilon 50}}{A_{tot}}\delta(\varepsilon_{50})_n + \frac{A_b}{A_{tot}}\delta b_n\end{pmatrix} \\ &= (A_{tot})\begin{pmatrix}(F_{EI})\,\delta(EI)_n + (F_c)\,\delta c_n + (F_{\gamma'})\,\delta\gamma'_n \\ + (F_{\varepsilon 50})\,\delta(\varepsilon_{50})_n + (F_b)\,\delta b_n\end{pmatrix}\end{aligned} \quad [6]$$

where (F_{EI}), (F_c), $(F_{\gamma'})$, $(F_{\varepsilon 50})$, and (F_b) are the sensitivity factors representing the relative contribution of the indicated design variables to the total change of maximum generalized deflection of member-pile when subjected to constant load.

4. NUMERICAL INVESTIGATIONS

The numerical investigations of sensitivity performance of laterally loaded pile group embedded in p-y soft clay below the water table subjected to cyclic loading are based on Eq. 3. In particular, the middle member-pile of the second trailing row is taken for detailed sensitivity analysis. This member-pile differentiates mostly from the analogous single isolated pile, and this fact justifies its choice for sensitivity investigation.

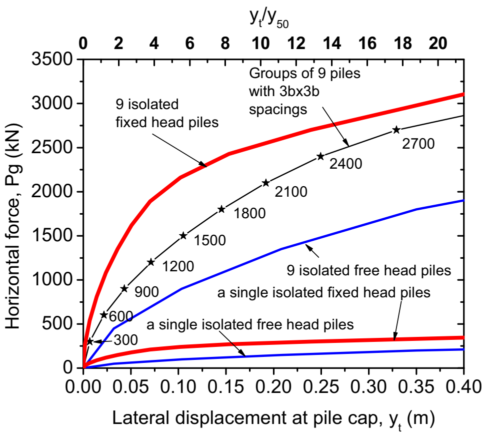


Figure 3. Horizontal forces Pg vs pile head lateral displacements y_t.

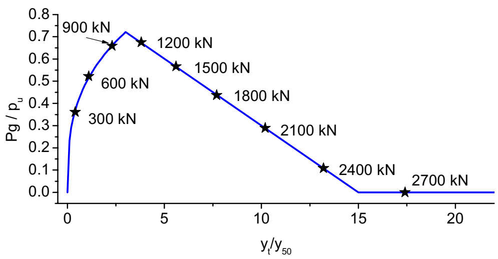


Figure 4. Soil reaction p at the soil surface vs. lateral displacement of a second trailing member-pile (Pile A) generated by the lateral loadings Pg applied to the pile group cap.

The objectives of the numerical sensitivity investigations are:

• The determination of the distributions of sensitivity operators $C_{(...)}$ along the member-pile axis for the discrete values of lateral force Pg applied to the cap of fixed head pile group.

• The quantitative assessment of sensitivity performance of the top lateral deflection due to the changes of the design variables.

The pile group consists of 9 long member-piles having length L=9T (equal to L=22.4 m) where T (equal to 2.49 m) is the relative stiffness factor (Evans and Duncan, 1982). The member-piles are arranged in the group 3x3 with equal spacing s in both directions, being equal to 3b. The b is the width of the pile and it is equal to 373 mm (Fig. 2). The member-piles are steel H piles with cross-section taken as 14HP89 that have EI=74,800 kNm^2 and are connected to the cap with fixed type connections. The parameters of soil p-y relationships are specified as follows: the cohesion c=18 kPa, the effective unit weight γ'=7.89 kN/m^2 and the strain ε_{50}=0.02 as it is recommended by Wang and Reese (1993). The p-multipliers f_m reflecting the pile group effect are taken as f_{t2}=0.58, f_{t1}=0.67, f_{tL}=0.82 (Mokwa and Duncan, 2001). The previously specified properties are used in the numerical analysis of the pile group by means of the Finite Element Method (FEM) program FB-Pier (2001).

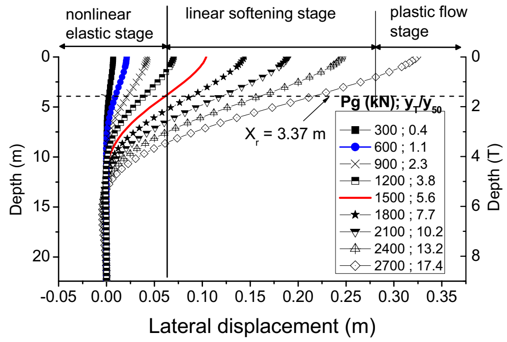


Figure 5. The distribution of lateral displacement along the pile A.

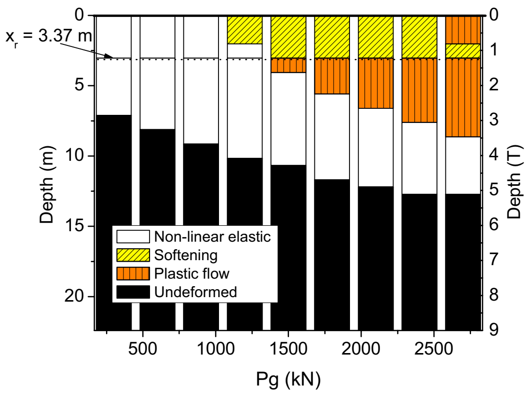


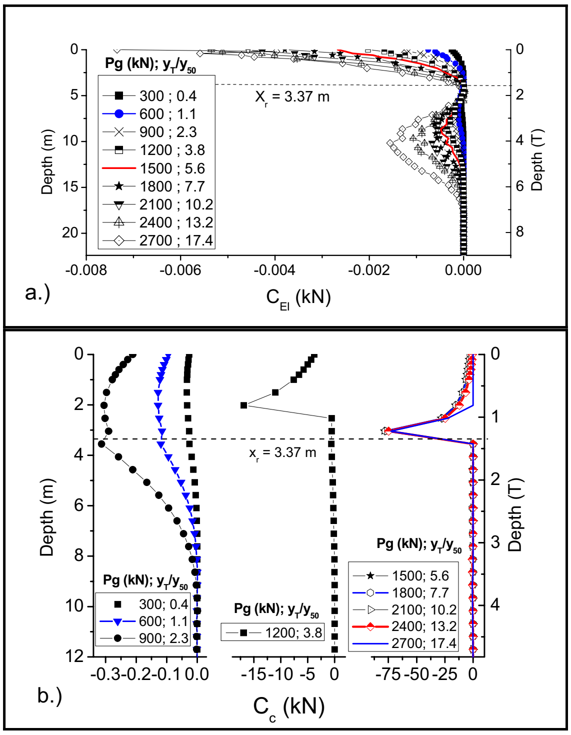
Figure 6. The distribution of the soil stages along the depth for the pile A due to the horizontal force Pg.

The sensitivity investigations of the pile group embedded in the non-linear p-y soft clay located below the water table are conducted in the vicinity of the applied load that is maintained constant and allowing for arbitrary changes in the design variables. The variability of the applied load Pg is introduced in a discrete fashion. The cap of primary pile group is subjected to a series of lateral forces Pg that increase from 300 kN to 2700 kN. The results of investigations in terms of horizontal forces applied vs. the lateral deflections at the pile head are shown in Fig. 3. This figure presents also for comparative purposes other diagrams that enables one to explore the following scenarios:

1. p vs. lateral deflection y_t for the free head single isolated pile,
2. p vs. lateral deflection y_t for the fixed head isolated pile,
3. Pg applied to a group of 9 fixed head isolated piles (s>6b) vs. y_t,
4. Pg applied to a group of 9 free head isolated piles (s>6b) vs. y_t,
5. Pg applied to a group of 9 fixed head piles (3bx3b spacing) vs. y_t.

The comparison of the response of the pile group system and the group of 9 single fixed head piles shows how the group effect reduces the capacity (strength) of the system. The comparative analysis of scenarios 3 and 4 aims at showing the effect of pile head type connections on the capacity of the piles. The fixed type connections (scenario 5) with pile cap give a considerably greater capacity than free type connections to the pile cap, even after applications of the multipliers to the fixed head pile group. The characteristics of the primary pile group system are transferred also to the adjoint pile group system (Haugh et al., 1986).

The lateral deflection y_t of the pile group cap when subjected to force Pg of discrete variability (for values 300 kN-2700 kN) are transferred to the corresponding p-y curve for x=0. The results of this operation are shown in Fig. 4. Figure 4 allows noticing that the p-y model at the soil surface is in the non-linear elastic stage when Pg (300 kN – 900 kN); linear softening stage at the same point occurs when Pg (1200 kN - 2400 kN); plastic flow starting at x=0, when Pg (≈2700 kN).



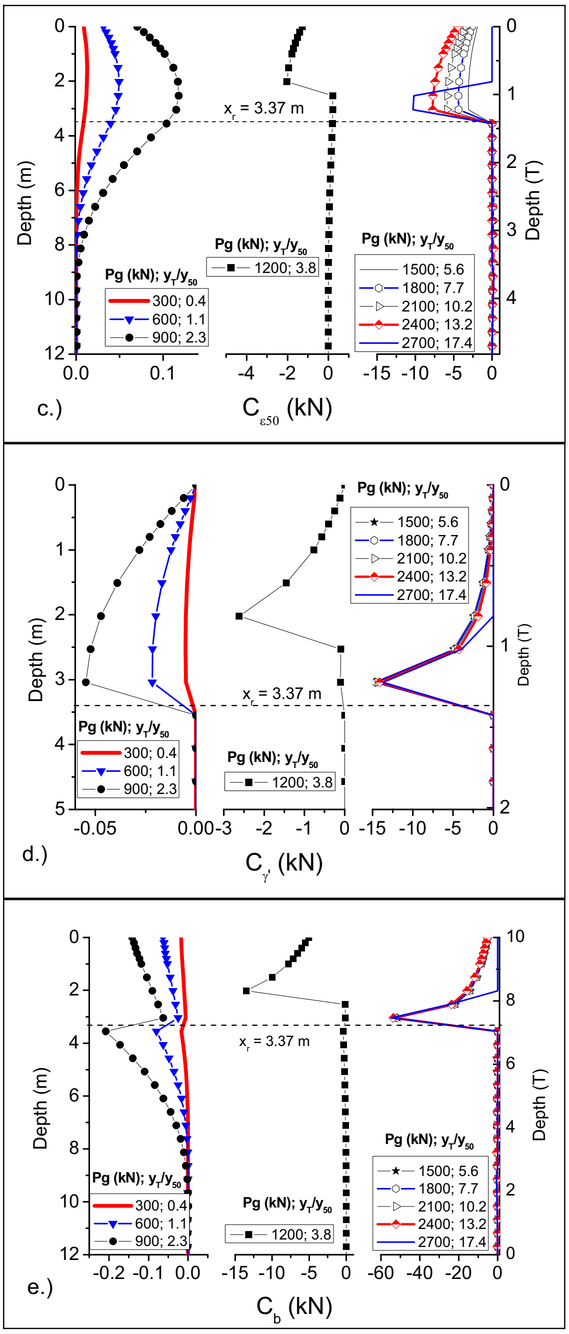


Figure 7. The distributions of the sensitivity operators a.) C_{EI}; b.)C_c; c.)$C_{\varepsilon 50}$, d.)$C_{\gamma'}$; and e.) C_b along the depth for the pile A.

The distributions of the lateral responses of the middle second trailing row member-pile (pile A in Fig. 2) due to the series of lateral forces Pg (with marked physical p-y soil stages developed) are presented in Fig. 5. Consequently, the evaluation of the p-y soil stages developed along the pile length for discrete values of Pg applied to the pile group cap are shown in Fig. 6.

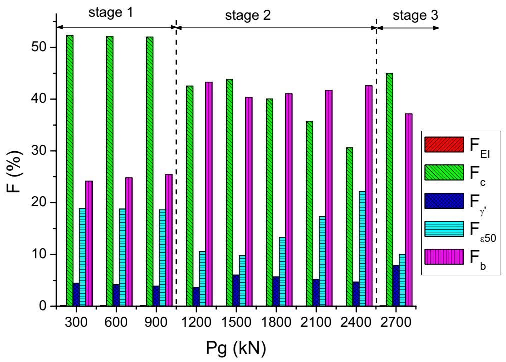


Figure 8. The distribution of the sensitivity factors F for pile A due to horizontal force Pg applied at the pile group.

5. DISCUSSION OF THE SENSITIVITY RESULTS

The characteristics of the sensitivity operators $C_{(...)}$ of each member-pile of the pile group subjected to Pg of discrete variability are similar in qualitative sense. The differences are of quantitative type (Priyanto, 2002).

In this paper the distributions of $C_{(...)}$ for pile A of Fig. 2 (middle member-pile of the second trailing row) are presented. Physically, each value of $C_{(...)}$ at arbitrary depth describes the effect of the change of the particular design variable on the change of the lateral displacement at the pile cap. The higher is the value of a sensitivity operator $C_{(...)}$ at a particular depth x, the higher is the effect of the change of the design variable on the changes of lateral displacement.

The distributions of the sensitivity operators C_{EI}, C_c, $C_{\gamma'}$, $C\varepsilon_{50}$, and C_b for the middle member-pile of the second trailing row (pile A Fig. 2) are presented in Fig. 7 (7a-7e). The distributions of sensitivity operators $C_{(...)}$ show certain locations and magnitudes of $C_{(...)}$ where the improvement of the performance of the system is most effective. The variability of sensitivity operator C_{EI} along the depth (Fig. 7a) is a function of the response of the primary and adjoint structure in terms of their internal bending moments; thus, the shape of C_{EI} is cognate to the products of bending moment of primary and adjoint member-pile. Characteristically, the behaviour of the pile structure is not affected by the development of various p-y soil stages along the depth as illustrated in Fig. 6. The magnitudes of C_{EI} increase with increase of the value of horizontal forces applied to the pile cap Pg.

Unlike in the pin joint pile where the bending moment response is equal to zero at the pile cap (Budkowska and Priyanto, 2003b), in the fixed joint pile head the maximum value of the bending moment is around the pile cap. Consequently, the maximum sensitivity operator C_{EI} is also located around the pile cap. The beneficial effect of the improvement of bending stiffness EI on the pile head deflection is only effective up to the depth of ≈ 7T (17.5 m).

The geometrical shape of the distributions of the sensitivity operator C_c (Fig. 7b) is highly dependable on the soil deformation stage. When the soil is in the non-linear elastic stage (Pg = 300 kN - 900 kN), the shape of the distribution of sensitivity operator C_c follows a particular type. Then, when the soil experiences a linear softening (Pg=1200kN - 2400kN), the sensitivity operator C_c increases rapidly at the point that describes the transition from the non-linear elastic stage to the linear softening stage. The distributions of C_c at this stage show that when the p-y soil medium is in the linear softening stage, the change of the cohesion c affects very strongly the change of the lateral deflection of the pile head. When the plastic flow occurs (Pg≈2700 kN), the changes of the cohesion c of that part of the soil medium being in plastic flow does not affect the changes of the lateral displacement y_t of the pile head. This fact is associated with the non-uniqueness of p-y relationship. The change of the cohesion c affects the performance of δy_t up to the depth of 3T (about 7 m) for Pg(300 kN - 900 kN) and up to the depth of 1.5T (about 3.5 m) for Pg (1500 kN - 2700 kN).

The distributions of sensitivity operators $C_{\varepsilon 50}$ (Fig. 7c) have similar characteristics as C_c except the sign convention in the elastic stage. The small difference in the shape of geometrical curves C_c and $C_{\varepsilon 50}$ is observed when the p-y soil model is in linear softening stage.

The positive sign of $C_{\varepsilon 50}$ for the non-linear elastic soil stage means that the increase of the ε_{50} generates larger deflection y_t. In the elastic stage it denotes the weakness of the soil. There is no considerable change in the sensitivity operators C_{EI}, C_c, and $C_{\varepsilon 50}$ at the depth x_r in the non-linear elastic stage. It demonstates that these sensitivity operators are independent of the depth x_r.

The distributions of the sensitivity operator $C_{\gamma'}$ (Fig. 7d) only exist up to the depth of x_r; they are equal to zero for the depth below x_r. The $C_{\gamma'}$ distributions show that the changes of γ' only affect the lateral displacement of y_t up to the depth x_r. They also indicate significant increment when the p-y soil is in the transition from the non-linear elastic stage to the linear softening stage, and they are equal to zero at the plastic flow.

In the non-linear elastic soil stage the distribution of the sensitivity operator C_b (Fig. 7e) is dependent on the depth x_r and its magnitude increases significantly at the depth x_r. The sensitivity operator C_b is also highly dependent on the soil-stage; its magnitude increases considerably when the soil stage changes from the non-linear elastic to the linear softening and it is equal to zero when the plastic flow occurs. The change in the C_b only affects the lateral displacement response up to the depth of approximately 3T (8m) for small values of Pg (300 kN – 900 kN). When the lateral load Pg increases (1200 kN – 2700 kN), the effect of change of b on y_t extends up to the depth 1T~1.5T.

The determination of the relative sensitivity factors given by Eq. 6 is performed by conducting numerical integrations of Eq. 3 using Simpson's rule. The contribution of change of each design variable to the relative change of lateral displacement y_t (expressed in %) is represented by the sensitivity factors F. They are shown in Fig. 8 in reference to the lateral load Pg applied. Figure 8 shows also the p-y soil stages developed at the soil surface when the force Pg of a specific value is applied to the pile group cap.

In Fig. 8, the values of the lateral forces Pg are classified into three stages. The stage 1 (for Pg = 300 kN - 900 kN) shows that the pile-soil-pile system only contains one soil phase (non-linear elastic p-y stage); in stage 2 (for Pg = 1200 kN - 2400 kN) the soil can reveal two phases (non-linear elastic and linear softening), while being in stage 3 the three soil phases are able to develop (non-linear elastic; linear softening and plastic flow). Figure 8 shows that in the stage 1, the sensitivity factors F are almost independent of the magnitude of the lateral force Pg. In the stage 2 and 3, the sensitivity factors F are altered with the magnitude of the lateral force Pg due to the development of combination of various soil phases having different length along the member-pile. In all of the stages the contribution of the sensitivity factors F to the changes of the pile head lateral deflection y_t when assessed from the most significant to the least significant are: the cohesion c, the width b where the soil reaction can develop, the ε_{50}, the submerged unit weight γ', and the bending stiffness of the pile EI. This classification allows for the reasonable selection of the most important design variables that affect the changes of the performance of the pile group.

6. CONCLUSIONS

The presented numerical investigations of sensitivity of laterally loaded pile group embedded in p-y soft clay located below the water table subjected to cyclic loading lead to the following conclusions:

1. The performance of the pile group when subjected to constant value of load Pg is sensitive to the changes of the parameters that define the behaviour of the system,
2. The sensitivity theory of distributed parameters demonstrates that the changes of the performance of the system depend on the location of the changes of the design variables of the system,
3. The sensitivity of the performance of the pile group embedded in p-y soil caused by the changes of the design variables is strongly dependent on the magnitude of the load Pg applied to the pile group cap,
4. The sensitivity of the performance of the pile group embedded in p-y soil due to the changes of the design variables increases very significantly when the load Pg allows for development of linear softening and plastic flow in the p-y soil,
5. The quantitative assessment of the effect of the changes of the design variables on the changes of the performance of the system on the scale from most significant to least significant is: the cohesion c, the width b where the soil reaction p is developed, the ε_{50}, the submerged unit weight γ' and the bending stiffness of the pile EI.

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