JOURNAL OF ENGINEERING AND APPLIED SCIENCE, VOL. 67, NO. 6, DEC. 2020, PP. 1343-1361
FACULTY OF ENGINEERING, CAIRO UNIVERSITY

TIME PERIOD CALCULATIONS FOR TALL BUILDINGS ON PILED-RAFTS INCLUDING SOIL-STRUCTURE INTERACTION EFFECTS

A. F. FARID[1], M. M. EL GALAD[2] AND Y. F. RASHED[3]

ABSTRACT

The purpose of this paper is to compute time period for tall buildings rested on piled-rafts including soil-structure interaction effects. The pile-pile, pile-soil and soil-soil interactions are considered through the development of two-iteration based coupling procedures between the super and sub-structures. The super-structure is modeled using any commercial finite element software, whereas the sub-structure including the building foundation is modeled using a developed boundary element software (PLPAK). It was demonstrated that the consideration of soil-structure interaction greatly increases the time period and consequently reduces the seismic design forces.

KEYWORDS: Time period, Piled-raft foundation, Soil-structure interactions, Tall buildings.

1. INTRODUCTION

In different building codes, the calculation of the base shear due to lateral loads is dependent on the time period of the considered building, as well as soil, ductility, building importance factors, etc. Building codes proposed different approximate formulae to calculate the building time period. It has to be noted that the computed values are only dependent on the building height, neglecting the building dimensions and stiffness as well as the effect of the soil flexibility. Equations (1, 2) represent a calculated time period (T) for a building of height (h) according to the ASCE 7-10 (12.8-7) [1] and Euro code EC8

[1] Lecturer, Department of Structural Engineering, Cairo University, Giza, Egypt, ahmedfadyfarid@eng1.cu.edu.eg
[2] Ph.D. Candidate, Department of Structural Engineering, Cairo University, Giza, Egypt.
[3] Professor, Department of Structural Engineering, Cairo University, Giza, Egypt.

[2] respectively. It is to be noted that the Egyptian Code of Practice (ECP 201-2012) [3] also uses Eq. (2).

$$T = C_t \times h^x \tag{1}$$

$$T = C_t \times h^{3/4} \tag{2}$$

Where C_t and x are parameters dependent on the type of seismic resistance of the building whether it is a steel or a concrete building.

The first category of researchers tried to modify the empirical formula (1, 2). Others tried to introduce new empirical formulae (the second researchers' category). The first category such as the work of Kwon and Kim [4] tried to modify the empirical formula in Eq. (1) by analyzing over 191 buildings of different types of resisting systems and recorded over 67 earthquakes within the time period 1970 till 2008. They measured the time period of these buildings and compared it to values obtained based on Eq. (1). They recommended changing the factor C_t to be a lower value for buildings with multiple resisting systems [4]. Dunkerley proposed alternative formula given by Eq. (3) for a multi-story building of (n) floors each as (m) mass rested on fixed base, as follows [5]

$$\frac{1}{\omega_1^2} = \sum_{j=1}^{n} \frac{1}{k_j} \sum_{i=j}^{n} m_i \tag{3}$$

Where ω_1 represents the lower bound of the natural frequency of the building and k_j is the lateral stiffness of floor number j. Luco [6] modified Dunkerley's formula [5] as given by Eq. (4) to take into account the translational, rotational and coupling effect of rigid foundation on a flexible soil as follows

$$\frac{1}{\omega_{1T}^2} = \frac{1}{\omega_1^2} + \frac{1}{\omega_{f1}^2} + \frac{1}{\omega_{f2}^2} \tag{4}$$

Where ω_{1T} is the total natural frequency, whereas ω_{f1} and ω_{f2} are the natural frequencies of the translation and rotation stiffness including the effect of soil-structure interaction. In order to determine the value of ω_{1T} in Eq. (4) an iterative process is performed as the values of ω_{f1} and ω_{f2} are dependent on the foundation stiffness.

Xiong et al. performed experimental tests on steel frames including the effect of one soil type and compared the measured time period to results obtained from finite element analysis using the commercial package (SAP2000) to validate Luco formula [6] given by Eq. (4) experimentally [7].

The second researchers' category on the other hand, such as the work of Hatzigeorgiou and Kanapitsas, introduced a new empirical formula given by Eq. (5) to calculate the building time period [8] as follows

$$T = \frac{h^{C_1} W^{C_2} (C_3 + C_4 F)}{\left[1 - e^{C_5 k_s^{C_6}}\right] \sqrt{(1 - C_7 \rho)}} \tag{5}$$

Where C_1, C_2, C_3, C_4, C_5, C_6, C_7 are constants and are equal to 0.745, 0.024, 0.073, -0.021, -0.706, 0.20, 0.043 respectively, h is the building height, m, W is the width of the building along considered direction, m, F is equal to 0 in case of using frames and equals 1 in case of infill walls. K_s is the soil stiffness in MN/m^3, ρ is the ratio between the shear walls area along the seismic direction to the total areas of the shear walls. Equation (5) was based on 3D finite element modelling for 20 real buildings taking into consideration the effect of soil, which was represented as Winkler springs. The number of floors for these buildings ranges from three to ten floors (low to mid-rise buildings).

Currently, designers use numerical software programs to calculate the time period for buildings using one of the following approaches: The first approach is to model the super-structure on fixed supports ignoring the soil-structure interaction effects [9]. The disadvantage of this approach is that the computed time period is very small. Hence, such an approach overestimates the computed seismic forces.

The second approach is to model the super-structure together with the foundation that typically is modeled resting on Winkler springs to represent soil and piles. This approach was introduced by Horvath in 1983 [10] till the work of Colasanti and Horvath in 2010 [11]. Despite this methodology being fast, it is not accurate as the stiffness values of the soil springs is dependent mainly on the first soil layer. Besides the effect of soil – soil, soil – pile and pile – pile interactions are neglected. Generally, the computed time period based on this approach is a bit lower than the actual one. This will also lead to overestimating the seismic design loads.

The third approach is to model the soil underneath the super and sub-structure as a three dimensional continuum model. The super-structure is modeled as shell and skeletal elements; whereas the foundation is modeled as thick or thin plate to represent the raft. The soil is modeled as 3D solid elements. Even though, this approach is accurate; it requires huge computer storage and huge computational time. Therefore, it is not practical.

The fourth approach such as the work of Hemsley [12] considers the effect of the soil – structure interaction using an iterative approach to couple both the super and sub – structures. The overall building is divided into two parts: the first part is the super-structure including the building and raft foundation, whereas the sub-structure consists of the soil that is modeled as elastic half space. The idea of this approach starts from modeling the 3D model for the superstructure (the building and the raft) supported on virtual stiffness springs. The coupled spring reactions are then applied as external loads in another geotechnical software that can model the soil as elastic half space (EHS); hence, the deformation underneath each load or spring is determined. A new value of stiffness for each spring is computed. Then the super-structure is reanalyzed to obtain the new spring reactions. These iterations are repeated until the spring stiffness approaches constant values. This approach requires about 12 to 15 iterations (this is dependent to the number of degrees of freedom of the soil) which means that the time of analysis and computation is high. This approach is currently used in design companies.

Jeong and Cho considered the effect of the soil – structure interaction for a piled-raft foundation [13] as an extension of Hemsly approach [12]. The piles are modeled as beam elements and soil – pile interaction are modeled as spring using nonlinear load transfer curves. The purpose of the study was to determine the final settlement behavior of the piled-raft building without getting through the computations building time periods.

Elmeiligy and Rashed proposed an alternative iteration technique [14] to Hemsley [12]. In their work [14], the super-structure is modeled as the building without raft rested on springs (i.e. separating the super-structure at the top level of the raft). The sub-structure contains the raft together with the soil, which is modeled as thick plate over elastic half space. Similar iterative techniques to Hemsely [12] are carried out between the considered sub-structures to compute the building time period. The advantage of the method [14] is decreasing the number of iterations to only two due to the reduction of the numbers of degrees of freedom. However buildings rested on piled-rafts were not considered.

In this paper, an extension to the methodology proposed by Elmeliegy and Rashed [14] is developed to treat building over piled-raft foundations. All interaction effects are considered. The super-structure is modeled using finite element method (using any commercial software). The sub-structure is modeled as a piled-raft together with the soil, which is modeled as thick plate over elastic-half space (EHS). The pile-pile, pile-soil and soil-soil interactions effects are computed and considered. The boundary element software (PLPAK) [15] is used to benefit from its capability of importing any additional stiffness to the plate system of equations. In this paper, the interaction effects (pile–soil and pile–pile) are added as additional stiffness to the PLPAK software. In section 2, pile-pile and pile-soil interaction effects calculations are presented. The implementation of these effects, in addition to its effect on the time period of tall buildings are presented in section 3.

2. INTERACTION EFFECTS

In case of applying a certain load on a group of piles embedded into the soil as shown in Fig. 1, pile deformation is calculated from deformation of the pile itself in addition to the additional soil–pile and pile–pile deformation of the pile group. The additional deformation of pile–pile interaction can be determined from either elastic approach based on Mindlin’s solution [16] or by load transfer approach based on Randolph’s empirical equations [17].

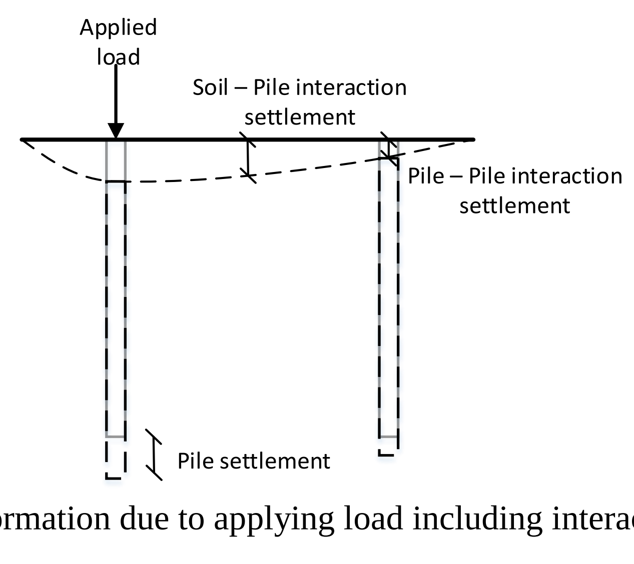

Fig. 1. The deformation due to applying load including interaction effects.

Each pile is modeled as cylindrical elements, each with constant friction along its surface. In addition to two circular elements at its two extreme nodes to simulate the end bearing at the bottom contact with soil and at the coupling degree of freedom postulated at the top intersection with the raft area as shown in Fig. 2.

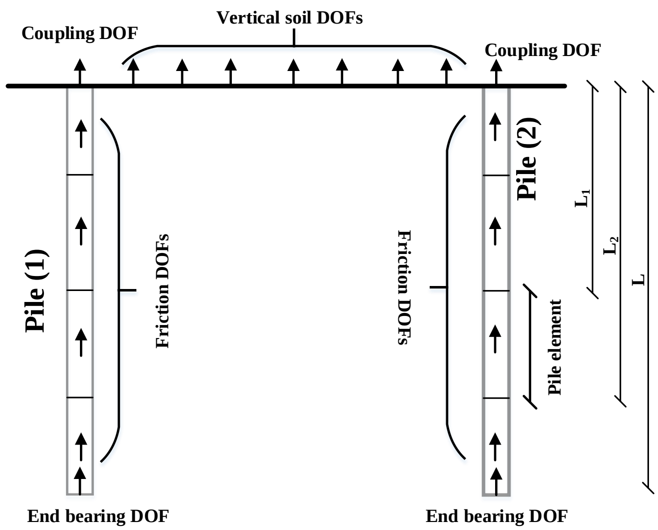

Fig. 2. Degrees of freedom of piles-soil system.

The flexibility matrix of pile–pile interaction effects, shown in Fig. 3, can be divided into three main flexibility coefficients. The first contains all off – diagonal friction elements (**F_{cf}, F_{ce}, F_{fe}, F_{fc}, F_{ec} and F_{ef}**) which could be computed either from Mindlin's solution [16] as in Eq. (6), or from Randolph's solution [17], as given in Eq. (9).

$$[F_{PP}] = \begin{array}{c|c:c:c|} & \text{Coupling DOFs} & \text{Friction DOFs} & \text{End bearing DOFs} \\ \hline \text{Coupling DOFs} & F_{cc} & F_{cf} & F_{ce} \\ \hdashline \text{Friction DOFs} & F_{fc} & F_{ff} & F_{fe} \\ \hdashline \text{End bearing DOFs} & F_{ec} & F_{ef} & F_{ee} \\ \hline \end{array}$$

Fig. 3. Flexibility matrix of the pile-pile interaction effects.

$$f_{ij} = \frac{1}{16\,\pi\,G\,(1-\upsilon)}\left[\frac{(3-4\upsilon)}{R_1} + \frac{8(1-\upsilon)^2-(3-4\upsilon)}{R_2} + \frac{(Z-C)^2}{R_1^3} + \frac{(3-4\upsilon)(Z+C)^2-2CZ}{R_2^3} + \frac{6CZ(Z+C)^2}{R_2^5}\right] \quad (6)$$

Where Z is the depth of load point (i), C is the depth of displacement-calculated point (j), R_1 and R_2 are calculated from Eqs. (7, 8) respectively, υ is soil Poisson's ratio and G is soil shear modulus.

$$R_1 = \sqrt{s^2 + (Z - C)^2} \quad (7)$$

$$R_2 = \sqrt{s^2 + (Z + C)^2} \quad (8)$$

In which $s = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$, x_i, y_i and x_j, y_j are the plan coordinate for load coordinate and displacement calculated coordinate respectively.

$$f_{ij} = \frac{1}{G}\sum_{i=1}^{np} (r_0)_i \ln\left(\frac{r_m}{S_{ij}}\right) \quad (9)$$

Where r_o is the radius of the pile, S_{ij} is the distance between the two points (i, and j), and r_m is the radius of influence for the piles and its value can be computed from Eq. (10) [16]

$$r_m = 2.5\, l_t\,(1 - \upsilon) \quad (10)$$

Where l_t is the total length of the pile.

Equation (11) is used to compute coefficients of end bearing in both cases. The subscripts e, c, f mean end bearing, coupling, and friction degrees of freedom respectively.

$$f_{ij} = \frac{(1-\upsilon)}{2\,\pi\,G}\sum_{i=1}^{np}\frac{1}{S_{ij}} \quad (11)$$

The second flexibility coefficients are the diagonal coefficients of the friction degrees of freedom (**F_{ff}**), in this case either the integrated Mindlin's solution over the pre-mentioned cylindrical element is used as in Eq. (12), or Randolph's empirical Eq. (13) could also be used.

$$f_{ij} = \frac{1}{2\pi r_0 l}\int_0^{2\pi}\int_{l1}^{l2} f_{ij} r_0\, dl\, d\theta \quad (12)$$

Where l_1 and l_2 are start and end points of loaded element, l is the pile element length as shown in Fig. 2.

$$f_{ij} = \frac{\tau_0 r_0}{G}\ln\left(\frac{r_m}{r_0}\right) \quad (13)$$

The third stiffness coefficients are of the end bearing (**F_{ee}**) together with those corresponding to the integrated coupling degree of freedom (**F_{cc}**) obtained based on Mindlin's solution over circular element (as in Eq. (14)), or the Randolph's equation as in Eq. (15).

$$f_{ij} = \frac{1}{\pi r_0^2} \int_0^{2\pi} \int_0^{r_0} f_{ij} r_0 dr d\theta \tag{14}$$

$$f_{ij} = \frac{(1-\upsilon)}{4\, r_0\, G} \tag{15}$$

In order to determine the interaction effects for pile-soil (**F_{PS}**) and soil–soil (**F_{SS}**) interactions, the soil continuum is discretized into rectangular surface elements (boundary elements) with only vertical degree of freedom. Mindlin's Eq. [16] (recall Eq. (6)) is used to obtain the flexibility matrix for these interactions.

Based on the previous equations, the total stiffness matrix [K] is calculated from the inverse of the flexibility matrix [F] that includes all interaction effects (pile–pile, pile–soil, and soil–soil interactions) as shown in Fig. 4. The PLPAK software [15] has a unique capability to import any stiffness matrices. Therefore it is used in this work to read the stiffness matrix that includes all interaction effects [K] and add it to the system of equations of the modeled raft (which is previously modeled in the PLPAK). Now the piled-raft foundation includes both the reaction of the vertical elements from the super-structure as loads, and the stiffness matrix that represent all interaction effects. The deformation underneath the super-structure vertical elements can be obtained. In the next section, the proposed iterative technique and the calculation of the time period for the overall building is discussed.

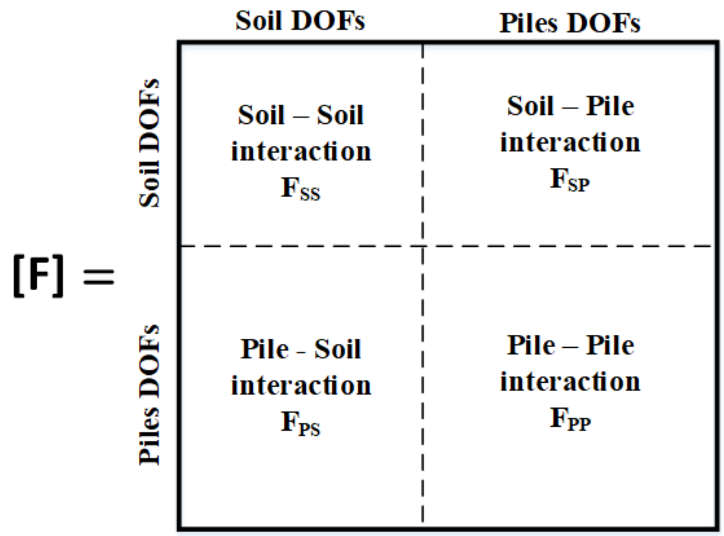

Fig. 4. Flexibility matrix of the overall system including all interaction effects.

3. THE PROPOSED EXTENSION

In this section, an extension of the work of Elmeliegy and Rashed [14] is presented. This extension is mainly implemented to add the effect of piles in computing the time period of a building. This is done by sub-structuring the overall building at the vertical elements interface with the foundation as shown in Fig. 5. The overall building includes two models: the first model is for the super-structure which is rested on fixed supports and is solved using any commercial software. This is to obtain the reactions of the vertical elements at the sub-structuring level. The second model, on the other hand, is for the sub-structure and is solved using software (PLPAK). The raft is modeled as thick plate, the piles are modeled as circular supporting areas, and the soil is modeled as internal supporting areas. The interaction effects between piles and soil (pile-pile, pile-soil, and soil-soil) are computed in an externally written computer code (as mentioned in section 2) and imported to the PLPAK software as stiffness matrix.

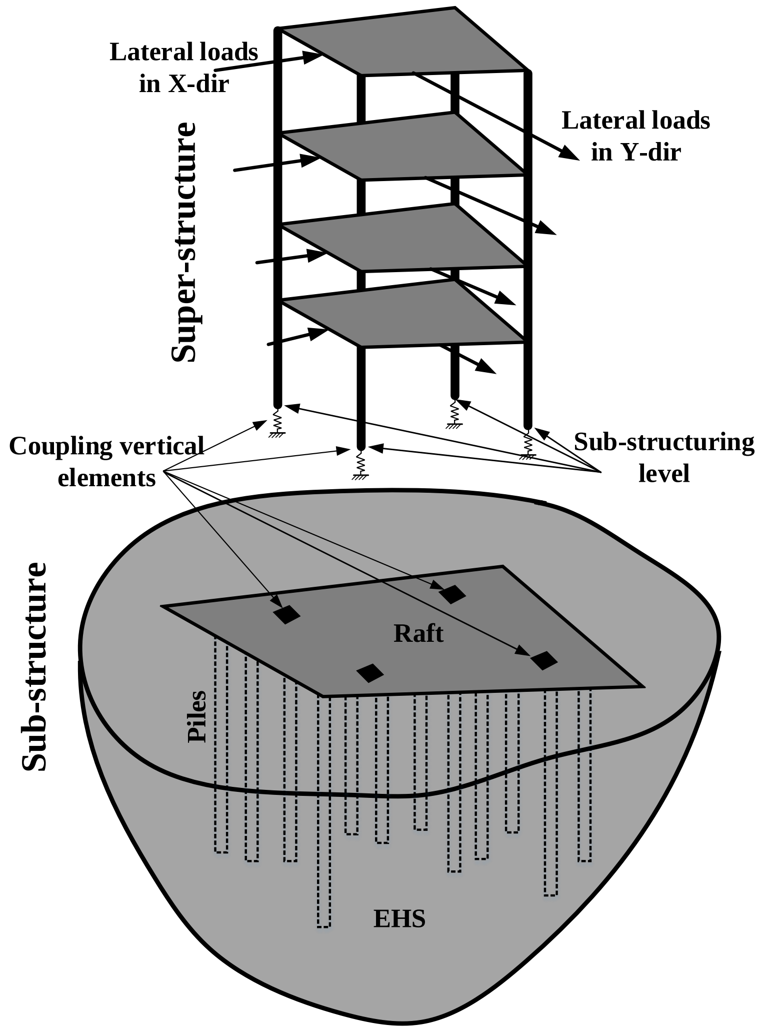

Fig. 5. The proposed sub-structuring technique of the super and the sub-structures.

The time period calculations for a piled-raft building including soil-structure interaction effects is presented as follows: the first step is to carry out the 3D modelling for the super-structure on fixed base using any finite element commercial software where the slabs and shear walls are modeled as shell elements, while columns and beams are modeled as frame elements. An initial analysis without lateral loads for determining the time period of the super-structure is carried out. From the value of the computed time period the lateral loads can be initially calculated according to any used design codes (for example ACI, EC, ECP, etc.). In contrast to the lateral load, the dead and live loads are not affected by the value of the computed time period. Then the model is reanalyzed, after adding the lateral load values, to obtain the reactions of the vertical elements at the sub-structuring level.

The second step is applying the computed reactions as loads in the PLPAK model that includes the raft foundation, piles and soil. The stiffness matrix for pile–pile, pile–soil, and soil–soil interactions are calculated as mentioned in section (2) and hence is inserted to the PLPAK software to obtain the deformation underneath the loads due to vertical elements. From the loads and deformation, a spring stiffness is computed to replace the fixed support in the first step.

The third step is updating and reanalyzing the super-structure after replacing the fixed support with springs. Then a new value of time period is obtained based on the consideration of the effect of soil–pile interactions and consequently new values of lateral load are updated. The previous steps are repeated till the time period becomes nearly constant (usually two iterations are enough for convergence). The flow chart presented in Fig. 6 summarizes these steps. These steps are carried out for lateral load in X and Y directions. It is to be noted that the soil and piles stiffness matrix including interaction effects is calculated only one time in the analysis.

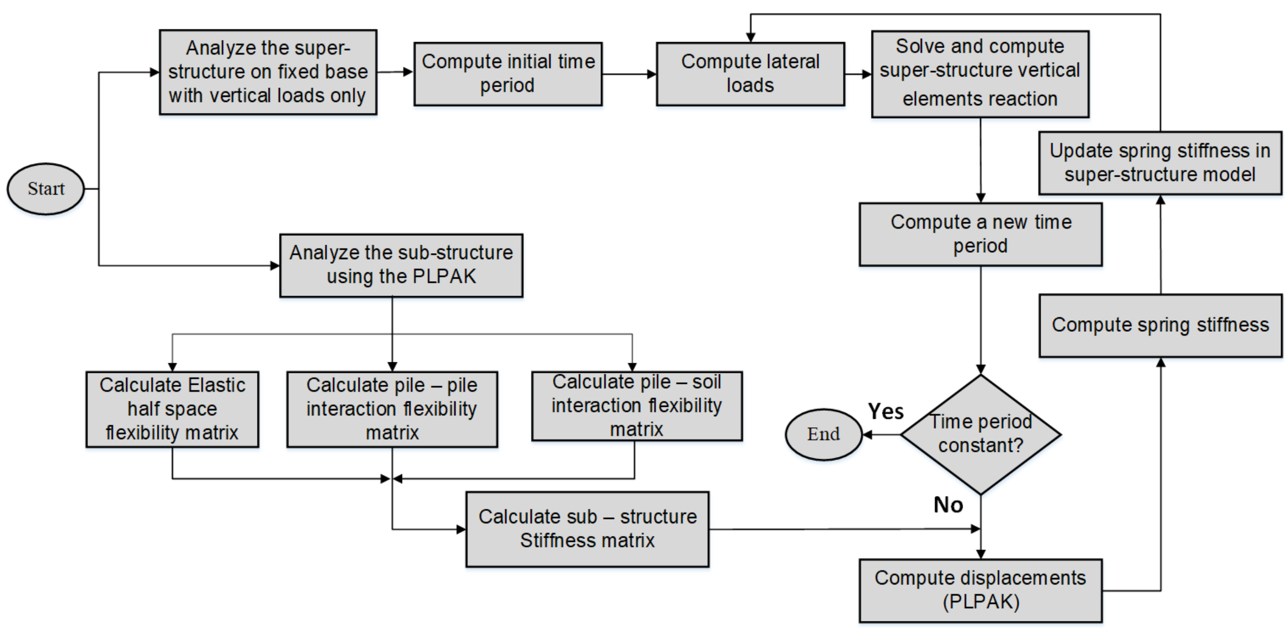

Fig. 6. Flow chart of time period calculations of piled-raft building.

4. NUMERICAL EXAMPLE

In this section, the verification example shown in Fig. 7 is considered. This example is solved three times to represent 10, 15 and 20 typical floors considering the analysis in X-direction only. Shear walls (solid black lines in Fig. 7) are assumed with these size to fulfill the ECP 201 [3] code requirement with restriction (time period shall not exceeds 4 seconds). The building is rested on piled-raft foundation as shown in Fig. 8. Five different analytical models are demonstrated for the purpose of comparison and to demonstrate the effect of considering the soil–structure interaction:

1- Model (1): 3D finite element model for the super-structure supported on fixed supports as shown in Fig. 9. This model is commonly used in the design offices. In this model floors, columns/beams, and walls/cores are modeled as plate, frame, and shell elements respectively.

2- Model (2): 3D finite element model for the super-structure as in model (1). The piles are represented by Winkler springs; the stiffness values of the piles are obtained from the Egyptian code of practice for deep foundations (ECP 202/4) [18]. This is done by calculating the allowable capacity divided by the allowable settlement of a single pile.

3- Model (3): Using manual calculations as time period is computed based on the empirical Eq. (5) according to Hatzigeorgiou and Kanapitsas [8].

4- Model (4): 3D finite element model for both the super-structure (as shell and frame elements) and for the sub-structure (raft as 4-node shell elements, soil as 8-node solid elements and piles as frame elements). The three translation DOFs of the shell element node are compatible with the corresponding three translation DOFs in the solid element. However, the two rotations DOFs in the shell element will not transmitted to the solid elements, because the soil does not transmit rotations, in addition these DOFs are transmitted through the shell elements. Piles were modeled as frame elements linked through the depth of the solid element (soil) and linked to the shell elements at nodes (raft). The soil block dimensions under the raft are 57 × 58 × 15 m. The solid elements discretization is taken 1.0 ×1.0 ×1.0 m under the foundation and is transmitted to be 2.0 ×2.0 ×1.0 m outside the foundation using transition elements as shown in Fig. 10. Piles are discretized into 1 m element along its length. Displacements are prevented in the far field, and rigid layer is added at 15 m depth.

5- Model (5): similar to model (4) but with finer solid element mesh in which the mesh is doubled.

6- Model (6): represents the present work solution by coupling the super and sub-structures as proposed in section 3. Figure 11 demonstrates the piled-raft boundary element model with loads from (reactions of) super-structure vertical elements.

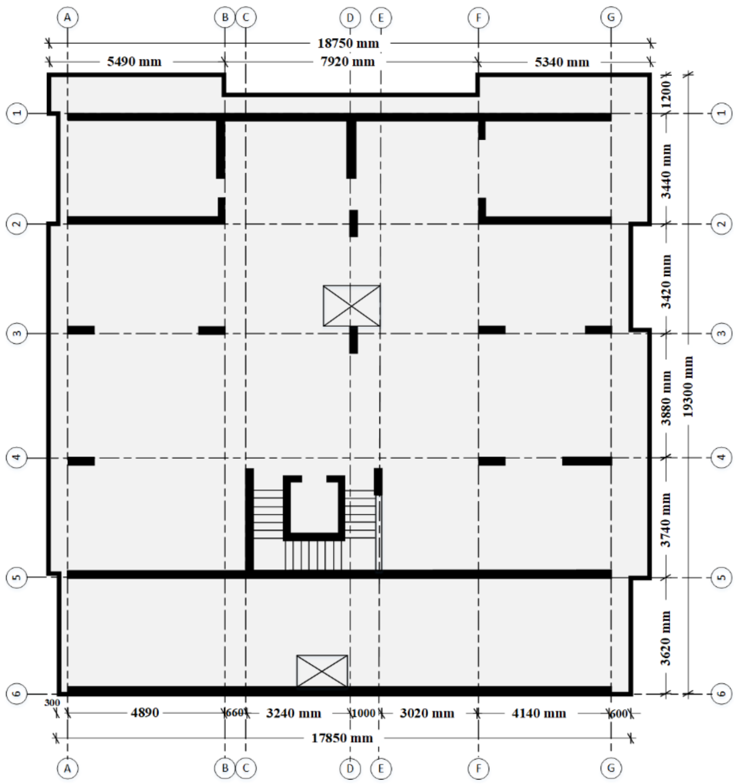

Fig. 7. The verification example typical floor layout.

It has to be noted that, concrete strength (f_{cu}), Young's modulus (E_{conc}) and Poisson's ratio are 30 MPa, 24100 Mpa and 0.2 respectively. These values are obtained according to (ECP 202-2018) [19]. The soil Young's modulus (E_{soil}), Poisson's ratio and coefficient of subgrade reaction (K_{soil}) are 5 MPa, 0.4 and 0.025 MPa/mm respectively. These values are obtained from approximate values presented in the (ECP 202/03) [20]. The slab and raft thicknesses are 200 and 1200 mm respectively. The column (C_1), Wall (W_1) and (W_2) dimension are 250×800, 250×1500 and 250×2000 mm. The pile diameter and length are 500 and 10000 mm respectively. The seismic coefficients are taken as follows:

- Seismic zone factor is 0.125 g
- Importance factor is 1.00
- Resistance factor 5.00
- Soil type is a type (D), i.e. weak soil
- Damping factor is 1.00

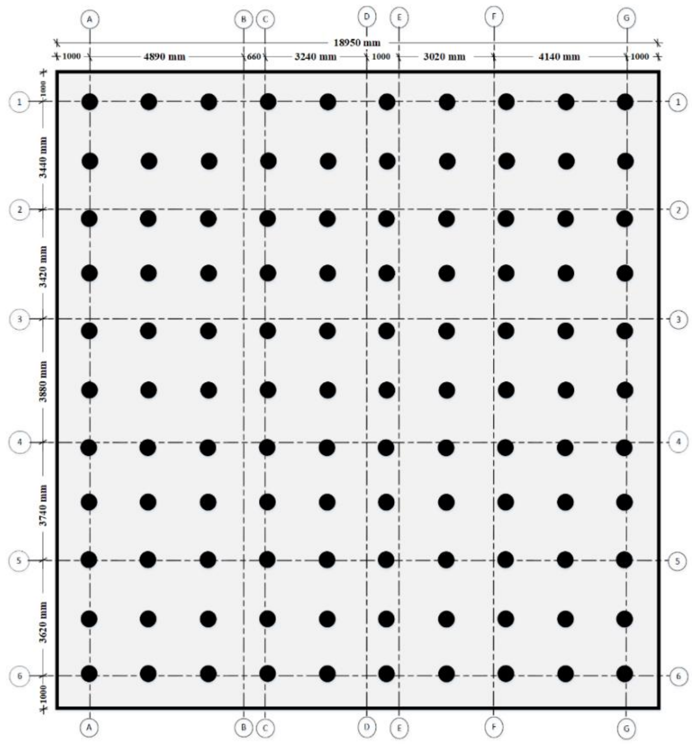

Fig. 8. The foundation piled-raft layout of the verification example.

The periodic time value for the five models with different number of floors is shown in Table 1. The value of the base shear according to the Egyptian code of practice (ECP 201-2012) [3] are demonstrated in Table 2. A major parameter besides the computation of base shear value is the time consumed to solve the problem. Table 3 demonstrates such a time for each model.

It can be seen that, the time period value for the above-mentioned models is dramatically changed by considering interaction effects. Building design code underestimates the value of the time period and consequently gives a high value of the design base shear. In addition, using Winkler springs to represent soil or piles still underestimate the value of the time period. Using Eq. (5) [8] gives better values than Winkler springs values however it still underestimates the values of the time period. The present model solution gives comparable results to those of the refined 3D finite elements analysis; however, the later consumes huge computational effort and time.

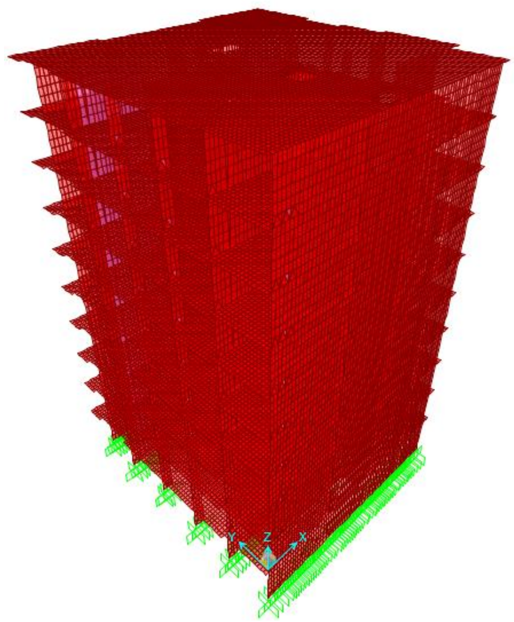

Fig. 9. Detailed 3D finite element model for fixed base super-structure (model 1).

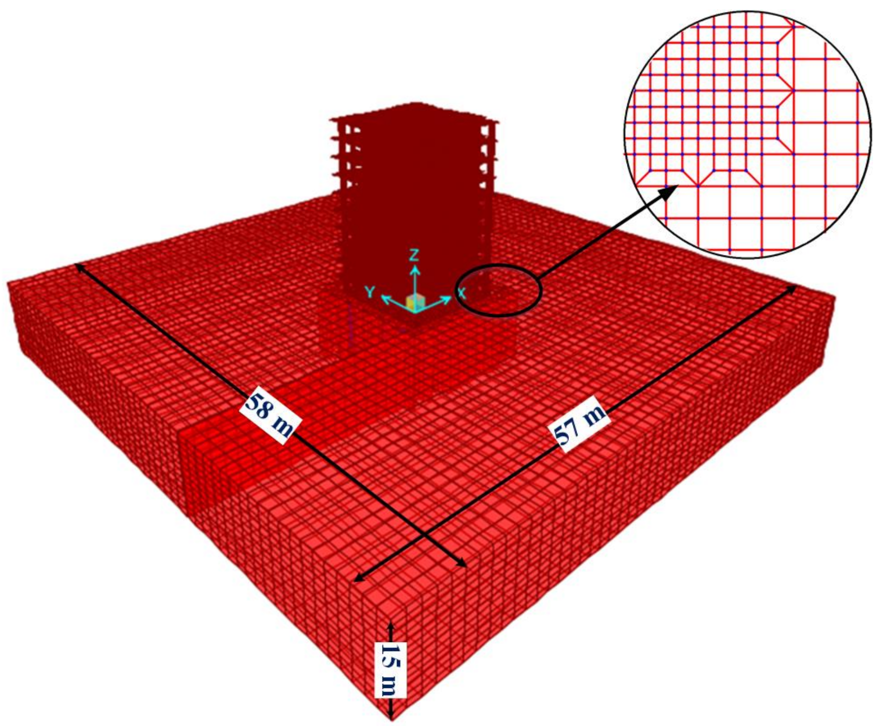

Fig. 10. Detailed 3D finite element model including soil as solid element (model 4).

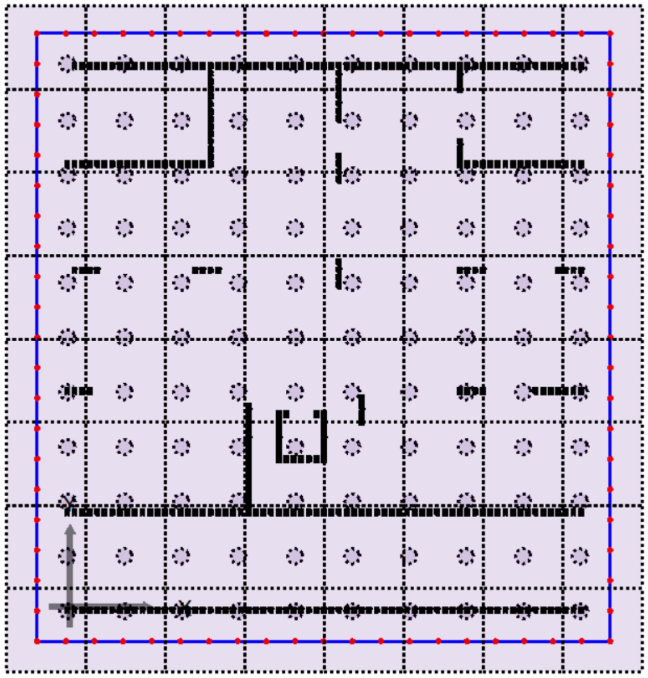

Fig. 11. Boundary element model for piled-raft with the vertical element reactions (model 6).

Table 1. The periodic time (in seconds) for the different models.

Number of floors	Value according to ECP code	Fixed base Model (1)	Winkler springs Model (2)	Equation (5) Ref. [8] Model (3)	3D solid elements 1×1×1 m Model (4)	3D solid elements 0.5×0.5×0.5 m Model (5)	Proposed technique Model (6)
10	0.64	0.93	1.63	1.33	2.97	2.85	2.72
15	0.87	1.28	1.89	1.80	3.71	3.35	2.95
20	1.07	1.77	2.25	2.23	4.15	3.93	3.81

Table 2. The base shear (in tons) for the different models.

Number of floors	Value according to ECP code	Fixed base Model (1)	Winkler springs Model (2)	Equation (5) Ref. [8] Model (3)	3D solid elements 1×1×1 m Model (4)	3D solid elements 0.5×0.5×0.5 m Model (5)	Proposed technique Model (6)
10	138.37	119	79.9	83.23	48.23	48.23	48.23
15	190.86	129.72	103.36	108.52	72.35	72.35	72.35
20	206.91	147.15	102.9	104.75	96.47	96.47	96.47

Table 3. The time (in minutes) for analysis of different models.

Number of floors	Value according to ECP code	Fixed base Model (1)	Winkler springs Model (2)	Equation (5) Ref. [8] Model (3)	3D solid elements 1×1×1 m Model (4)	3D solid elements 0.5×0.5×0.5 m Model (5)	Proposed technique Model (6)
10	---	5	5	---	240	1140	32
15	---	8	8	---	360	1400	40
20	---	12	12	---	480	1680	55

5. CONCLUSIONS

This paper presents the calculation of time period of tall buildings over piled-rafts taking into consideration the soil-structure interaction effects, such as soil–soil, soil–pile and pile–pile interactions. Super-structure was modeled using any commercial finite element software, whereas the soil was modeled as an elastic half space model, which is implemented in the boundary element software (PLPAK), the piles were modeled as a circular support area and the interaction effects were imported as stiffness in the used boundary element software. Time period calculation was carried out using an iterative technique. A verification example was presented and results demonstrated the effect of considering the SSI on calculating the time period. It was shown that the computed values differ by 292%, 230%, and 215% in the case of 10, 15, and 20 floors respectively compared to those obtained considering fixed base. This lead to decrease the base shear value to about 59.5%, 44%, and 34.5% for 10, 15, and 20 floors building respectively compared to those obtained considering fixed base. It has to be noted that the proposed technique computes values of the time period very close to the full 3D finite element model but with dramatically less computational time and effort. A designer can make use of the present work in this manuscript from the following link http://www.be4e.com/new/Iterative.html.

ACKNOWLEDGEMENTS

This project was supported financially by the Science and Technology Development Fund (STDF), Egypt, Grant No AHRC 30794. The first and third authors would like to acknowledge this support.

DECLARATION OF CONFLICT OF INTERESTS

The authors have declared no conflict of interests.

REFERENCES

1. ASCE, "Minimum Design Loads for Buildings and Other Structures", American Society of Civil Engineers, Virginia, USA, 2010.

2. EC8, "Eurocode 8 – Design of Structures for Earthquake Resistance. Part 1: General Rules, Seismic Action and Rules for Buildings", European Committee for Standardization, EN 1998 – 1, Brussels, Belgium, 2004.
3. ECP 201, Egyptian Code for Calculating Loads and Forces in Structural Work and Masonry", Housing and Building National Research Center, Ministry of Housing, Utilities and Urban Planning, Cairo, Egypt, 2012.
4. Kwon, O., and Kim, E., "Evaluation of Building Period Formulas for Seismic Design", Journal of Earthquake Engineering and Structural Dynamics, Vol. 39, pp. 1569-1583, 2010.
5. Dunkerley, S., "On the Whirling and Vibration of Shafts", Journal Philosophical Transaction of Royal Society, Vol. 185, pp. 279-360, 1894.
6. Luco, J. E., "Bounds for Natural Frequencies, Dunkerley's Formula and Application to Soil-Structure Interaction", Journal of Soil Dynamics and Earthquake Engineering, Vol. 47, pp. 32-37, 2013.
7. Xiong, W., Jiang, L., and Li, Y., "Influence of Soil – Structure Interaction (Structure-to-Soil Relative Stiffness and Mass Ratio) On the Fundamental Period of Buildings: Experimental Observation and Analytical Verification", Bulletin of Earthquake Engineering, Vol. 14, No. 1, pp. 139-160, 2016.
8. Hatzigeorgiou, G. D., and Kanapitsas, G., "Evaluation of Fundamental Period of Low-rise and Mid-rise Reinforced Concrete Buildings", Journal of Earthquake Engineering and Structural Dynamics, Vol. 42, No. 11, pp. 1599-1616, 2013.
9. Abdelwahab, M. A., Rashed, Y. F., and Mukhtar, A. A., "Time History Boundary Element Analysis of Multi Story Buildings", Journal of Engineering and Applied Science, Vol. 62, No. 2, pp. 165-185, 2015.
10. Horvath, J. S., "New Subgrade Model Applied to Mat Foundations", Journal of Geotechnical Engineering, Vol. 109, No. 12, pp. 1567-1587, 1983.
11. Colasanti, R. J., and Horvath, J. S., "Practical Subgrade Model for Improved Soil-Structure Interaction Analysis: Software Implementation", Practice Periodical on Structural Design and Construction", Vol. 15, No. 4, pp. 278-286, 2010.
12. Hemsly, J., "Elastic Solutions for Axisymmetric Loaded Circular Raft with Free and Clamped Edges Founded on Winkler Springs or a Half-Space", Proceedings of the Institution of Civil Engineers, Vol. 83, No. 1, pp. 61-90, 1987.
13. Jeong, S. J., and Cho, J., "Interactive 3D Analysis Method of Piled Raft Foundation for High – Rise Buildings", Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Vol. 18, pp. 2763-2766, 2013.
14. Elmeliegy, A. M., and Rashed, Y. F., "Efficient Preconditioned Soil-Foundation-Structure Interaction Approach to Compute Tall-Building Time Period", Journal American Society of Civil Engineers, Vol. 24, No. 3, pp. 1-13, 2019.
15. Rashed, Y. F., "A Boundary/Domain Element Method for Analysis of Building Raft Foundation", Journal of Engineering Analysis of Boundary Elements, Vol. 29, No. 9, pp. 859-877, 2005.

16. Wang, C. M., Chow, Y. K., and How, Y. C., "Analysis of Rectangular Thick Rafts on an Elastic Half Space", Journal of Computers and Geotechnics, Vol. 28, No. 3, pp. 161-184, 2001.
17. Randolph, M. F., and Worth, C. P., "Analysis of Deformation of Vertically Loaded Piles", Journal of Geotechnical Engineering Division ASCE, Vol. 104, pp. 1465-1488, 1978.
18. ECP 202, "Egyptian Code for Soil Mechanics Design and Construction of Foundations, Part 4, Deep Foundations", Housing and Building National Research Center. Ministry of Housing, Utilities and Urban Planning, Cairo, Egypt, 2005.
19. ECP 203, "Egyptian Code for Practice and Design of Concrete Structures, Housing and Building National Research Center, Ministry of Housing, Utilities and Urban Planning, Cairo, Egypt, 2018.
20. ECP 202, "Egyptian Code for Soil Mechanics—Design and Construction of Foundations, Part 3, Shallow Foundations", Housing and Building National Research Center, Ministry of Housing, Utilities and Urban Planning, Cairo, Egypt, 2005.

التأثير المتبادل بين التربة والمنشأ على حسابات الزمن الدوري للمباني العالية المرتكزة على لبش خازوقية

تم في البحث حساب الزمن الدوري للمباني العالية والتي ترتكز على لبش خازوقيه وبما في ذلك التأثير التبادلي بين التربة والمنشأ، شاملا التأثير التبادلي بين الخازوق والخازوق و بين الخازوق والتربة وبين التربة والتربة من خلال تطوير طريقة اقتران ثنائية التكرار بين المنشأ فوق وتحت سطح التربة حيث تم تمثيل المنشأ فوق سطح التربة باستخدام أي برنامج للحاسب يستخدم طريقة العناصر المحدودة، في حين يتم تمثيل المنشأ تحت سطح التربة بما في ذلك أساس المبنى باستخدام برنامج مطور يستخدم طريقة العناصر الحدودية (PLPAK) وقد ثبت أن أخذ التأثير المتبادل بين المنشأ والتربة في الاعتبار يزيد بشكل كبير من قيم الزمن الدوري للمنشأ وبالتالي يقلل من القوى التصميمية للزلازل.