Civil Engineering Infrastructures Journal, 47(2): 215 – 227, December 2014
ISSN: 2322 – 2093

A Simple Algorithm for Analyzing a Piled Raft by Considering Stress Distribution

Saeedi Azizkandi, A.R.[1*] and Fakher, A.[2]

[1] Ph.D. Candidate, Department of Civil Engineering, Iran University of Science and Technology, Tehran, Iran.
[2] Associate Professor, School of Civil Engineering, College of Engineering, University of Tehran, P.O.Box: 11155-4563, Tehran, Iran.

Received: 26 Nov. 2012; Revised: 21 Sep. 2013; Accepted: 30 Sep. 2013

ABSTRACT: Numerous techniques have been presented by different researchers to analyze piled raft. In order to analyze pile foundation, soil can be modeled as spring, continuous medium, or porous media. Pile can also be modeled as spring or continuous medium. This study includes three main stages: a short description of different types of analysis methods of pile foundation, writing a computer program based on the finite element method (FEM) for analyzing piled raft foundation (in this program, foundation is modeled as a flexible plate, soil and pile are modeled by Winkler springs), and comparison of different concepts of pile group design.

Keywords: Interaction, Piled Raft Foundation, Settlement, Stress Distribution, Winkler Spring.

INTRODUCTION

In order to build a structure, it is required to use a foundation to transfer applied load to soil. As well as load transfer function, foundations should be designed in a way that produced settlements, including uniform and non-uniform settlement, do not exceed the allowable limit.

Most of old buildings were built on a strip footing or single footing and if the ground surface layer were loose and compressible, timber pile would be used because of low wages and abundant wood resources. In addition, charcoal was used to provide abuoyant resistant layer in slough areas. However, as the weight and rigidity of buildings increased, in the eighteenth century, and also due to economic reasons, these methods, particularly timber piles, gradually lost their importance. In this condition, piles were used beneath the shallow foundation, where shallow foundation failed to resist applied load or where settlements exceeded the allowable limit.

The analysis of pile group behavior is conducted by making two basic assumptions, i.e. piled raft (free pile group) and free standing pile group. The first assumption leads to unreal increase of axial forces in the piles, while it is possible to design piles for fewer forces through considering the role of pile cap. If the soil below shallow foundation is loose or is affected by scouring, load-bearing share can

* Corresponding author E-mail: asaeedia@yahoo.com

be ignored and the total load will be undertaken by piles. The assumption of free pile group seems to be rational in such situations, whereas if the soil bellow the foundation is resistant, pile cap cooperates with piles to transfer load and a percentage of the load will be transferred by shallow foundation and the remainder by piles. Due to economic importance, this topic has been the focus of attention by various researchers and, consequently, different numerical programs have been developed in order to analyze the pile foundation.

ANALYSIS METHODS OF PILE GROUP

Before demonstrating analysis methods, it is necessary to clarify the concept of interaction factors used in the following part of this paper (Figure 1).

Interaction of pile-pile

$\alpha_{(P-P)}$=(Displacement of B pile due to applying unit load at A pile)/(Displacement of A pile due to applying unit load)

Interaction of soil-pile

$\alpha_{(S-P)}$=(Displacement of B pile due to applying unit surface pressure load at soil element)/(Displacement of the soil due to applying unit surface pressure load at soil element)

Interaction of pile-soil

$\alpha_{(P-S)}$=(Displacement of soil element due to applying unit load at A pile)/(Displacement of A pile due to applying unit loadt)

Interaction of soil-soil

$\alpha_{(S-S)}$=(Displacement of B soil due to applying unit surface pressure load at A soil element)/(Displacement of the soil due to applying unit surface pressure load at soil element)

In order to analyze and determine the settlement of piled raft, numerous methods have been proposed the elaboration of which is beyond the scope of this article. Thus, some of the important methods are mentioned in Table 1. Since the applicationof analysis methods among engineers depends on computer programs, the second column of Table 1 includes available computer programs to employ these methods.

Hooper (1973) used FEM with axial symmetry to design pile group for the first time and assumed that each concentric pile row can be replaced by a continuous ring with equivalent stiffness equal to total stiffness of soil and pile. He also converted a three-dimensional problem into a two-dimensional problem of plan strain- axial symmetry by applying a model with axis of symmetrical piles.

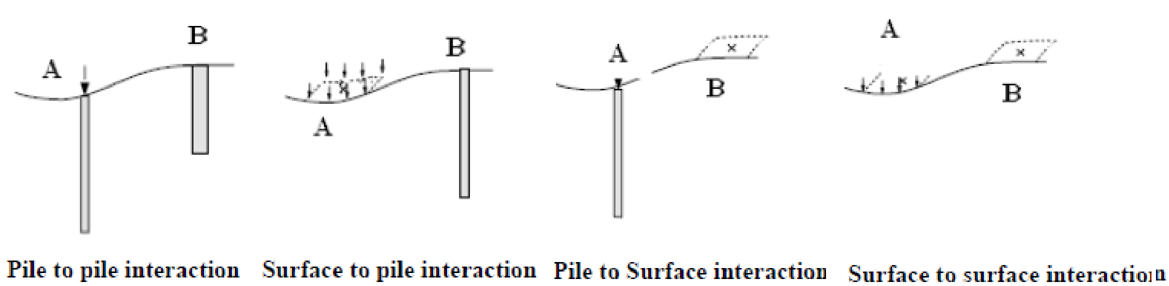

Fig. 1. Interaction factors (pile-pile, soil-pile, pile-soil, and soil-soil, from left to right, respectively).

Some additional explanations are presented about methods mentioned in Table 1: One of the methods to analyze piles is a numerical method based on the theory of elastic half space. Poulos (1996) proposed a numerical method employing finite difference method and the theory of elastic half space Boussinesq. In this model, he used a thin flexible plane in lieu of foundation and a series of equivalent springs by considering interaction factors between piles and continuous elastic medium instead of pile and soil respectively. This method is presented in GARP program (the fifth row of Table 1). In order to simplify the analysis procedure, each pile or pile group is modeled by a spring with equivalent stiffness (by considering interaction factor of pile-pile). The stiffness of equivalent spring is determined by separate analysis methods such as PIGLET and DEFPIG programs (the second and the first row of Table1 respectively) and will be used as inputs of GARP program. It is assumed that the module of soil changes linearly with depth. Poulos and Davis (2004) used the pile foundation. DEFPIG software was applied to determine the stiffness of pile and interaction factors between piles (input of GARP Software) and also to determine the behavior of pile group system against lateral loads.

As well as numerical methods, field tests were conducted to predict the behavior of piles, and the obtained results indicated a good agreement between results of numerical methods and field tests.

Table 1. Current analysis methods of pile group.

No.	Researcher	Program name	Type of soil modeling	Type of pile modeling	Comments
1	Poulos (1980, 1989)	DEFPIG	Freestanding pile group	Spring	Analysis of single piles, determination of equivalent stiffness of pile among pile group and by considering interaction of pile-pile
2	Randolph (1980)	PIGLET	Freestanding pile group	Spring	Output of the program is similar to DEFPIG program
3	Banerjee and Driscoll	PGROUP	Continuous medium	Continuous medium	Is more accurate than two above-mentioned but is time consuming and complicated
4	Poulos and Makarchian (1994)	AFENA	Continuous medium	Continuous medium	This program have been developed based on FEM with plane strain-axial symmetry
5	Poulos (1995)	GARP	Continuous medium	Spring	A short description is presented in the following
6	poulos (1996)	API	Spring	Spring	A short description is presented in the following
7	Commercial programs	FLAC – ANSYS	Continuous medium	Continuous medium	A short description is presented in the following
8	Commercial programs	SAP	Spring	Spring	Without considering interaction factors
9	Current research	Current program	Spring	Spring	With considering all 4 interaction factors

The principle of method used in API program (the sixth row of Table 1) was suggested by Poulos (1996). In this method, the first step is to determine the stiffness of foundation, pile and pile foundation. Then, the total load (P_t) will be distributed according to the stiffness of elements, and the settlement of piled raft will be determined. API uses the following equations to determine the above-mentioned parameters.

Pile stiffness: In order to determine pile stiffness, the proposed equation by Randolph (1987) is used.

Pile group stiffness: According to the stiffness of a single pile, pile group stiffness is calculated by Eq.1 proposed by Randolph (1987):

$$\mathrm{K_{PG}} = \mathrm{n}^{1-\mathrm{W}}.\ \mathrm{K_P} \quad (1)$$

where K_{PG}, K_P, n, and W are pile group stiffness, single pile stiffness, the number of piles forming pile group, and a factor related to type and distance between piles respectively. Poulos (1989) suggested the value of 0.3 to 0.5 for W.

Interaction factors: Interaction factors between pile group and mat foundation (α_{pr} and α_{rp}) are calculated by Eq.2.

$$\alpha_{rp} = \frac{Ln(r_m/n.r_0)}{Ln(r_m/r_0)} \qquad \alpha_{pr} = \alpha_{rp}\frac{\mathrm{K_r}}{\mathrm{K_{PG}}} \quad (2)$$

where K_r and r_m are total stiffness of the foundation and effect radius of produced shear stress respectively; and are calculated by the following equations.

$$K_r = \frac{E\,.\,t^3}{12\left(1-\mathcal{V}_r^{\,2}\right)} \quad (3)$$

$$r_m = 2.5\,\rho.l\,.(1-\mathcal{V}_s) \quad (4)$$

where E, t, v_r and ρ are Young module, thickness, Poisson's ratio of foundation and $\rho = G_{l/2}/G_l$ are change of shear module with soil depth respectively.

Pile foundation stiffness: regarding the stiffness of foundation and pile group and using proposed equations by Randolph and Wroth (1993), the stiffness of pile foundation and load-bearing share of foundation and pile group are calculated.

During recent years, full modeling of pile group, soil and pile cap by FEM has been the focus of attention due to increase of computational ability of computers. Although most of the methods deal with linear analysis, FEM showed comprehensive results in comparison to other methods. It should be noted that most of FEM were conducted in two dimensions, and three-dimensional analyses were avoided because they were time-consuming, particularly, in non-linear analysis. However, three-dimensional modeling of pile group and soil by FEM is common in research projects.

THE PROPOSED LINEAR ANALYSIS ALGORITHM OF PILED RAFT FOUNDATION

Idealization of Foundation, Soil and Pile

A program was developed based on FEM in Fortran Programming Language to determine settlement and load-bearing share of foundation and piles. In this program, foundation is modeled by a flexible plane with 4-node elements, and soil and piles are modeled by Winkler springs (Figure 2).

Separated equation of stiffness of pile foundation based on FEM is as follows:

$$K = K_r + K_s + K_p \quad (5)$$

K_p, K_s, K_r, and K are stiffness matrixes of pile, soil, flexible plate and total stiffness respectively and are determined as follows:

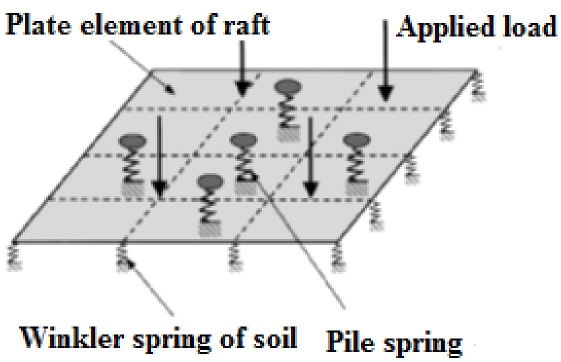

Fig. 2. FEM of a piled raft foundation.

Stiffness Matrix of Flexible Plate

In order to determine the stiffness matrix of a 4-node flexible plane, in which deflection of nodes includes vertical deflection (W) and rotation in the direction of x, y axis (θ_x, θ_y) (Figure 3), the following equation may be used:

$$K_r = \sum_{e} \int_{A^e} B^T.D.B.dA \tag{6}$$

where $\sum$, A, B, and D are sum operator, the area of one element, matrix of relation between deflection and strain, and matrix of characteristics of flexible plane respectively. The result of the above integration is K_r element presented in the following equation and matrix:

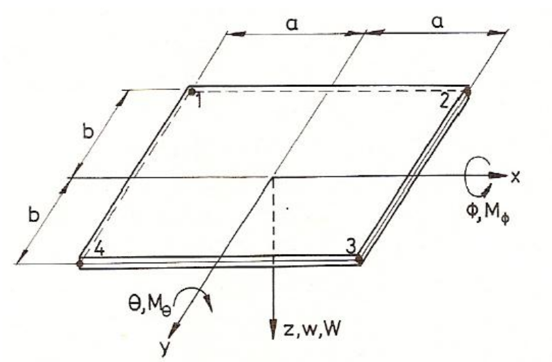

Fig. 3. Rectangular flexible element with freedom degree of 12

Stiffness Matrix of Piles by Considering Interaction between Pile-Pile and Pile-Soil

In order to determine the stiffness matrix of piles and stress distribution around each pile, it is essential to evaluate stiffness and stress distribution of pile shaft and pile base separately (Figure 4).

$$K^r = \frac{D}{60.a.b}\begin{bmatrix}
60P+60p^{-1}+42-12\nu & & & & & & & & & & & \\
b(60P+6+24\nu) & b^2(80P+16-16\nu) & & & & & & & & & & \\
a(60P^{-1}+6+24\nu) & 60\nu ab & a^2(80P^{-1}+16-16\nu) & & & & & & & & & \\
30P-60P^{-1}-42+12\nu & b(30P-6-24\nu) & a(-60P^{-1}-6+6\nu) & K_{1,1} & & & & & & & & \\
K_{4,2} & b^2(40P-16+16\nu) & 0 & K_{2,1} & K_{2,2} & & & & \textit{Symmetric} & & & \\
-K_{4,3} & -K_{5,3} & a^2(40P^{-1}-4+4\nu) & -K_{3,1} & -K_{3,2} & K_{3,3} & & & & & & \\
-30P-30P^{-1}+42-12\nu & b(-30P+6-6\nu) & a(-30P^{-1}+6-6\nu) & K_{10,1} & K_{10,2} & -K_{10,3} & K_{1,1} & & & & & \\
-K_{7,2} & b^2(20P+4-4\nu) & 0 & K_{11,1} & K_{11,2} & -K_{11,3} & -K_{2,1} & K_{2,2} & & & & \\
-K_{7,3} & K_{8,3} & a^2(20P^{-1}+4-4\nu) & -K_{12,1} & -K_{12,2} & K_{12,3} & -K_{3,1} & K_{3,2} & K_{3,3} & & & \\
-60P+30P^{-1}-42+12\nu & b(-60P-6+6\nu) & a(30P^{-1}-6-24\nu) & K_{7,1} & K_{7,2} & -K_{7,3} & K_{4,1} & -K_{4,2} & -K_{4,3} & K_{1,1} & & \\
-K_{10,2} & b^2(40P-4+4\nu) & 0 & K_{8,1} & K_{8,2} & -K_{8,3} & -K_{5,1} & K_{5,2} & K_{5,3} & -K_{2,1} & K_{2,2} & \\
K_{10,3} & -K_{11,3} & a^2(40P^{-1}-16+16\nu) & -K_{9,1} & -K_{9,2} & K_{9,3} & -K_{6,1} & K_{6,2} & K_{6,3} & K_{3,1} & -K_{3,2} & K_{3,3}
\end{bmatrix} \qquad P=\left(\frac{a}{b}\right)^2$$

$$D = \frac{E \cdot t^3}{12(1-\nu^2)} \tag{7}$$

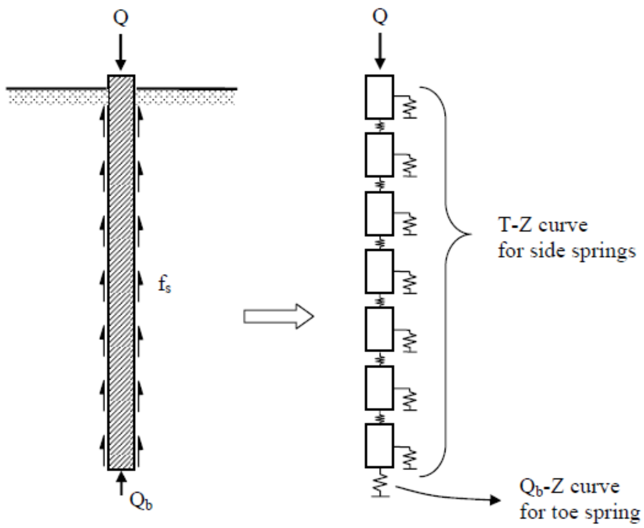

Fig. 4. Idealized model used in T-Z load transfer analyses.

Determination of the Pile Shaft Stiffness

The analysis of finite element method and boundary element method of friction pile reaction (Randolph, 1977) showed that load transfer through shear stresses produced on the horizontal and vertical planes. In general, a pile may be considered as an object surrounded by concentric cylinders of soil. Shear stress in each cylinder is equal (Randolph et al., 1978; Frank, 1974). By cutting sector-shaped pieces from two adjacent cylinders in soil (Figure 5) and writing equilibrium equation in the *y* direction, we may have:

$$\begin{aligned}&(\tau+\frac{\partial\tau}{\partial r}\cdot dr)\cdot\\&(r+dr)\cdot d\theta\cdot dy-\tau\cdot r\cdot d\theta\cdot dy\\&+(\sigma_y+\frac{\partial\sigma_y}{\partial y}\cdot dy)\cdot(r+\frac{dr}{2})\cdot d\theta\cdot dr\\&-\sigma_y\cdot(r+\frac{dr}{2})\cdot d\theta\cdot dr=0\end{aligned} \tag{8}$$

After simplifying and neglecting the second order terms, Eq. (8) reduces to:

$$\frac{\partial(\tau\cdot r)}{\partial r}+r\cdot\frac{\partial\sigma_y}{\partial y}=0 \tag{9}$$

However, according to Randolph and Wroth (1978), the rate of change of vertical stress with respect to depth is much less than the rate of change of shear stress with respect to radial distance during axial loading of pile. Therefore, the second term of Eq. (9) can be neglected, and the above equilibrium equation can be approximated as:

$$\frac{\partial(\tau\cdot r)}{\partial r}\approx 0 \tag{10}$$

Through integration of Eq. (10) and based on the assumption of homogeneous and elastic soil:

$$\begin{aligned}&\int_{r_0}^{r}d(\tau\cdot r)=0\Rightarrow\left[\tau(r)\cdot r-\tau(r_0)\cdot r_0\right]\\&=0\Rightarrow\tau(r)=\frac{\tau(r_0)\cdot r_0}{r}=\frac{\tau_0\cdot r_0}{r}\end{aligned} \tag{11}$$

where $\tau(r)$,$\tau_0=\tau(r_0)$ and r_0 are shear stress applied in the distance of r from the pile, produced shear stress between pile, soil, and pile radius respectively. The relation between shear stress and strain for linearly elastic soils is as follows:

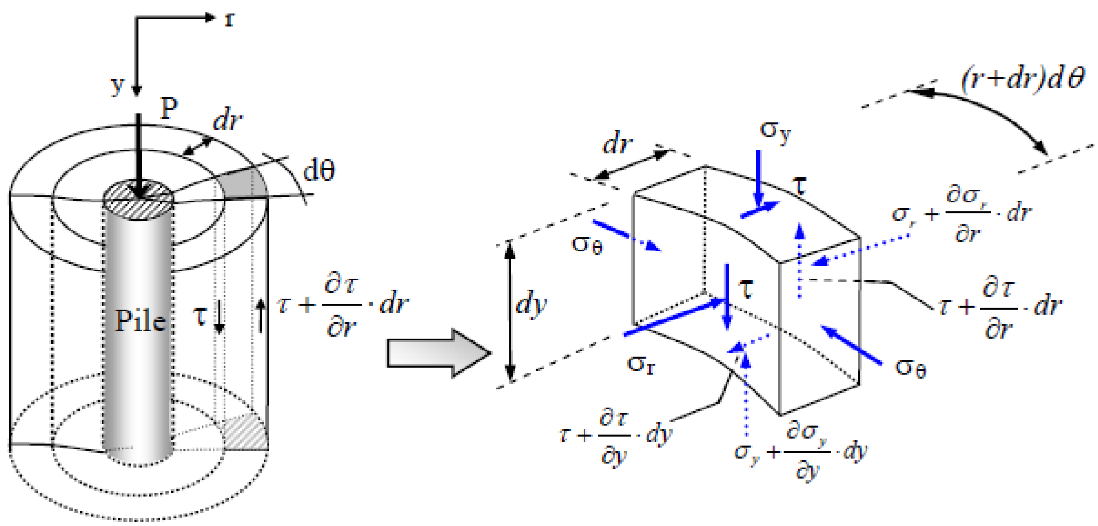

Fig. 5. Concentric cylinder model for settlement analysis of axially loaded piles.

$$\gamma(r) = \frac{dw}{dr} = \frac{\tau(r)}{G(r)} = \frac{\tau_0 \, . \, r_0}{r \, . \, G} \tag{12}$$

where W is vertical deflection in the distance of r from pile. Through integration of Eq. (12), deflection of pile shaft can be determined by Eq. (13). Change chart of T-Z is presented in Figure 6.

$$w_s = \tau_0 \cdot r_0 \cdot \int_{r_0}^{r_m} \frac{d(r)}{G \cdot r} = \frac{\tau_0 \cdot r_0}{G} Ln\left(\frac{r_m}{r_0}\right) \tag{13}$$

Determination of the Pile Base Stiffness

At the base pile, it is sufficient to ignore the pile shaft and surrounding soil, and treat the base as rigid punch acting at the surface of soil medium (in reality, it starts at the depth z=l). The deflection is obtained from Boussinesq equation (Eq. (14)). Change chart of Q_b-Z is presented in Figure 7.

$$W_b = \frac{Q_b(1 - \mathcal{V}_s)}{4 \, G \, r_0} \tag{14}$$

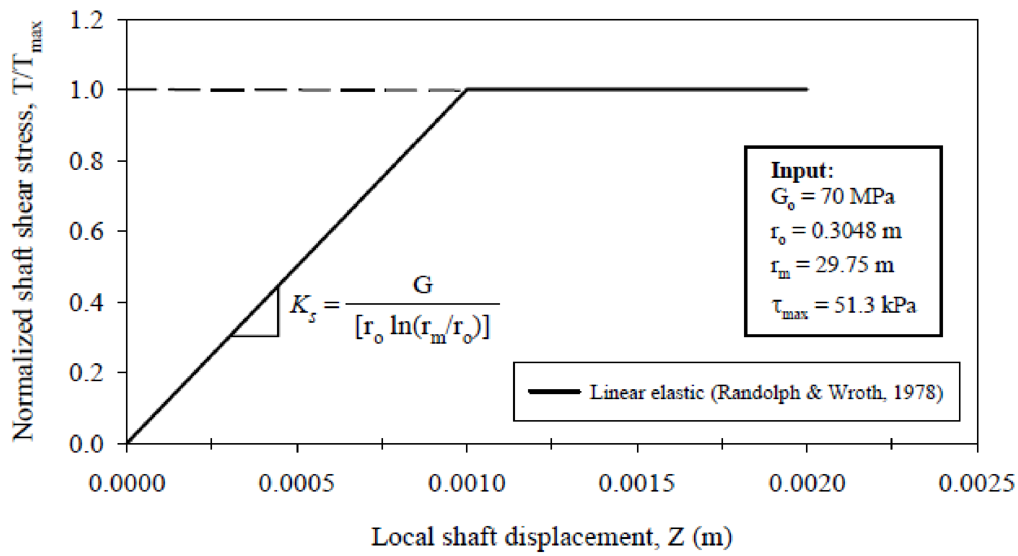

Fig. 6. Stiffness of pile shaft and change of shear stress along pile length.

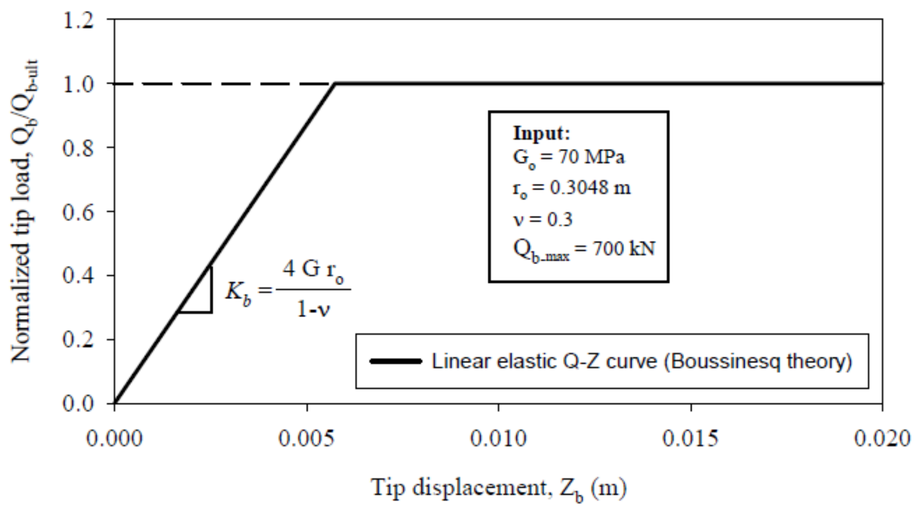

Fig. 7. Stiffness of pile base and change of bearing capacity of base by increase of pile length.

Based on what was mentioned, the sum of base settlement and pile axis settlement is equal to settlement of pile crest (W_t). Therefore, total load (P_t) may be written as follows:

$$P_t = P_b + P_s = W_t\left(\frac{P_b}{w_b} + \frac{P_s}{w_s}\right) \quad (15)$$

Hence, non-dimensional stiffness of a rigid pile can be calculated by using the following equation:

$$\frac{K_p}{G\,.\,r_0} = \frac{P_t}{w_t\, G\,.\,r_0} = \frac{4\,G\,.\,r_b}{G\,.\,r_0(1-\mathcal{V}_s)} + \frac{2\,\pi\,G\,l}{G\,.\,r_0} \quad (16)$$

Most of the piles show some axial compressibility due to the allowable load, and this should be considered during the calculation of pile stiffness. Thus, non-dimensional stiffness of pile is:

$$\frac{K_p}{G\,.\,r_0} = \frac{P_t}{w_t\, G\,.\,r_0} = \frac{\frac{4\eta}{(1-\mathcal{V}_s).\xi} + \frac{2\pi\rho.\tanh(\mu.l)}{\zeta.\mu.l.r_0}}{1 + \frac{4\eta.\tanh(\mu.l)}{\pi.\lambda(1-\mathcal{V}_s)\mu.l.\xi}\frac{l}{r_0}} \quad (17)$$

where $\eta = r_b/r_0$ (ratio of diameter increase for piles), $\xi = G_l/G_b$, $\rho = G_{l/2}/G_l$ (changes of shear module with depth), $\lambda = E_p/G_l$ (ratio of stiffness of soil to pile), $\zeta = Ln(r_m/r_0)$, $\mu.l = \sqrt{\frac{2}{\zeta.\lambda}}\left(\frac{l}{r_0}\right)$ (pile compressibility). In this program, if the value of $\frac{l}{r_0}$ is less than $0.5\sqrt{E_p/G_s}$, piles will be considered to be rigid and their stiffness will be calculated by using Eq. (16). Furthermore, if $\frac{l}{r_0}$ is greater than $3\sqrt{E_p/G_s}$, the value of $tanh(\mu.l)$ will approach unit and Eq. (17) will be approximately converted into Eq. (18).

$$\frac{K_p}{G\,.\,r_0} = \frac{P_t}{w_t\, G\,.\,r_0} = \pi\rho\sqrt{\frac{2\lambda}{\zeta}} \quad (18)$$

and if $0.5\sqrt{E_p/G_s} \le \frac{l}{r_0} \le 3\sqrt{E_p/G_s}$, Eq.17 will be used to determine pile stiffness. If load P is located on a pile, the deflection of a node in the distance of *r* from the load will be calculated by using Eqs. (19-20).

$$W_b = \frac{P_b(1-\mathcal{V}_s)}{2\pi GR} \quad (19)$$

$$W_s = \frac{P_s Ln(r_m/R)}{2\pi lG} \quad (20)$$

The ratio of bearing capacity of pile base (P_b) to total load (P_t) can be determined by Eq. (21).

$$A = \frac{P_b}{P_t} = \frac{\frac{4\eta}{(1-\mathcal{V}_s).\xi}\frac{1}{\cosh(\mu.l)}}{\frac{4\eta}{(1-\mathcal{V}_s).\xi} + \frac{2\pi\rho.\tanh(\mu.l)}{\zeta.\mu.l.r_0}} \quad (21)$$

Eqs. (19-21), the value of softness, due to interaction factors of pile-pile and pile-soil, is determined by using Eq. (22).

$$W_t = P_t\left(\frac{(1-A)Ln(r_m/R)}{2\pi\, l\, G} + \frac{A\,(1-\mathcal{V}_s)}{2\pi\, G\, R}\right) \quad (22)$$

The Stiffness Matrix of Soil Concerning Interaction of Soil-Soil and Soil-Pile

The stiffness matrix of soil concerned as Winkler spring is calculated through the following equation regardless of interaction.

$$K_S = \sum_e \int_{A^e} \acute{N}^T.K_S.N^T.dA \quad (23)$$

where K_s is Winkler springs constant factor and is determined by the proposed equation:

$$K_S = \frac{2.G_S}{B.(1-\mathcal{V}_s)} \quad (24)$$

where G_s, $\mathcal{V}_s$, and B are shear module, Poisson's ratio of soil, and foundation width respectively.

The softness, due to interaction factors of soil-soil and soil-pile, is calculated based on the Boussinesq equation as follows:

$$W_t = \frac{P_t(1-\mathcal{V}_s)}{2\pi GR} \quad (25)$$

As shown in Figure 8, the softness matrix of element (F), considering all interaction factors, is as follows:

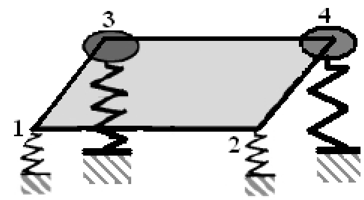

Fig. 8. An element of flexible plane with two nodes on soil (1,2) and two nods on pile (3,4).

Steps of Analyzing Mat Foundation on Pile Foundation

The first step: determination of stiffness matrix of flexible plane elements (pile cap) and their assembling and determination of stiffness matrix of total flexible plane.

The second step: determination of softness matrix of soil regarding interaction factors soil-soil and soil-pile.

The third step: determination of softness matrix of pile regarding interaction factors pile-pile and pile-soil.

The fourth step: assembling the softness matrix of pile and soil and calculating stiffness matrix by inverting the softness matrix.

The fifth step:assembling the stiffness matrix of soil and pile with stiffness matrix of flexible plane (pile cap) and calculating the deflection of piles through the relation of $F=K\,\Delta$ and bearing capacity of pile cap and pile.

PROGRAM VALIDATION

The proposed algorithm is quick and simple. However, it is required to evaluate the accuracy of results. In this section, the results, obtained from program, are validated through comparing the settlements with FLAC 3D model. Piled raft is shown in Figure 8. The characteristic of soil and pile foundation are given in Table 2. Moreover, element of pile cap is presented in Figure 9.

$$F=\begin{bmatrix} \frac{1}{K_S} & \frac{(1-\mathcal{V}_s)}{2\pi G R_{12}} & \left(\frac{(1-A)Ln(r_m/R_{13})}{2\pi\, l\, G}+\frac{A\,(1-\mathcal{V}_s)}{2\pi\, G\, R_{13}}\right) & \left(\frac{(1-A)Ln(r_m/R_{14})}{2\pi\, l\, G}+\frac{A\,(1-\mathcal{V}_s)}{2\pi\, G\, R_{14}}\right) \\ \frac{(1-\mathcal{V}_s)}{2\pi G R_{21}} & \frac{1}{K_S} & \left(\frac{(1-A)Ln(r_m/R_{23})}{2\pi\, l\, G}+\frac{A\,(1-\mathcal{V}_s)}{2\pi\, G\, R_{23}}\right) & \left(\frac{(1-A)Ln(r_m/R_{24})}{2\pi\, l\, G}+\frac{A\,(1-\mathcal{V}_s)}{2\pi\, G\, R_{24}}\right) \\ \frac{(1-\mathcal{V}_s)}{2\pi G R_{31}} & \frac{(1-\mathcal{V}_s)}{2\pi G R_{32}} & \frac{1}{K_P} & \left(\frac{(1-A)Ln(r_m/R_{34})}{2\pi\, l\, G}+\frac{A\,(1-\mathcal{V}_s)}{2\pi\, G\, R_{34}}\right) \\ \frac{(1-\mathcal{V}_s)}{2\pi G R_{41}} & \frac{(1-\mathcal{V}_s)}{2\pi G R_{42}} & \left(\frac{(1-A)Ln(r_m/R_{43})}{2\pi\, l\, G}+\frac{A\,(1-\mathcal{V}_s)}{2\pi\, G\, R_{43}}\right) & \frac{1}{K_P} \end{bmatrix}$$

Table 2. Characteristics of soil and pile foundation.

	Pile and Pile Cap	Soil
Young module (MPa)	2500	30
Poisson's ratio	0.2	0.35
Bulk module (MPa)	13900	33.33
Shear module (MPa)	10400	11.11
Cohesion (kPa)	-	50
Internal friction angle (constant)	-	30

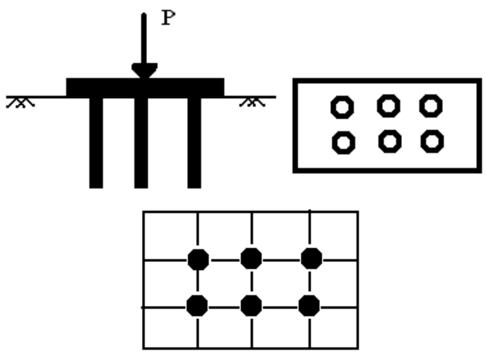

Fig. 9. Schematic shape of piled raft foundation.

In the current model, dimension of pile cap is 5.5×7.5 m, pile cap thickness is 1 m, and diameter and length of employed piles are 1 and 10 m, respectively. The piles are located in two rows of three piles. Also, normal load equal to 5000 kN is distributed uniformly across the areas of pile. The results of comparison are presented in Table 3.

According to Table 3, results of the proposed model have a good agreement with results obtained from FLAC 3D. However, it should be noted that the running time of FLAC 3D model for solving the above example was about 2 days, whereas the running time of the proposed program was about 2 minutes. Thus, the applied algorithm is quick and simple.

COMPARISON OF CONVENTIONAL AND NEW VIEWPOINTS PILED RAFT DESIGN

In the conventional methods of foundation design, the first step is to control the bearing capacity and settlement of mat foundation. If the settlement of mat foundation exceeds the allowable settlement, pile group will be used in lieu of mat foundation. Most of the conventional methods ignore load-bearing share of pile cap and the number of piles will carry total load. Therefore, the number of employed piles is more than required. From the economic perspective, produced settlement in the mat foundation should be limited within the allowable settlement. The new method for designing of pile group is called reducing-settlement pile foundation. Figure 10 shows different concepts of settlement-load curve for designing of pile group.

In Figure 10, curve number 1 shows the behavior of mat foundation (without pile). Produced settlement is more than the allowable limit. Therefore, piles are used to reduce settlement. Curve number 2 shows the conventional concept in the design of pile group. In this method, piled raft is designed in a way that a notable portion of the load is carried by piles. Curve number 3 represents the application of piles to reduce settlement.

Table 3. Comparison of results obtained from current program and FLAC 3D model.

	FLAC 3D	Proposed Program	Error Percentage of Program Compared with FLAC 3D
Settlement of intermediate piles (cm)	14.5	13.2	8.9%
Settlement of piles (cm)	12.6	12.95	1.6%
load-bearing share of pile cap	27%	34%	7%

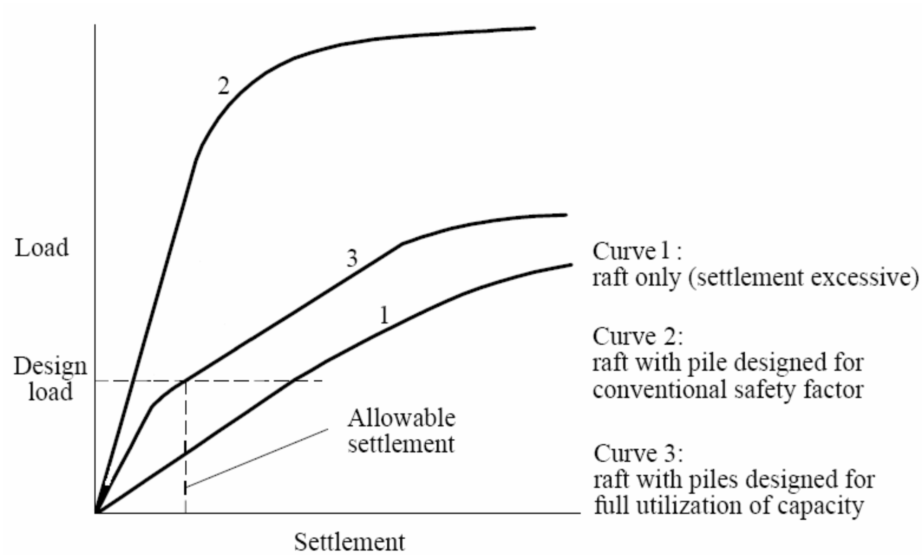

Fig. 10. Different concepts of settlement-load curve to design of pile group.

A Case Study to Compare Two Viewpoints New and Conventional

In this section, a piled raft load of 30,000 kN, the allowable settlement of 7 cm and a squared-shaped pile cap and thickness of 1m are designed by both new and conventional methods. The characteristics of soil and pile are given in Table 4.

Table 4. Characteristics of soil and pile.

Specification	Pile and cap	Soil
Young module (MPa)	2500	13
Poisson's ratio	0.2	o.3
Bulk module (MPa)	13900	10.83
Shear module (MPa)	10400	5
Cohesion (KPa)	-	70
Internal friction angle	-	5

Shallow Mat Foundation

Bearing capacity is calculated based on the characteristics of soil and Eq. (26):

$$q_u = 0.867\ \mathrm{c}\ \mathrm{N}_{c\gamma} \Rightarrow q_u = 0.867 \times 70000 \times 5.7 = 345 \times 10^3\ {}^{N}/_{\mathrm{m}^2} \qquad (26)$$

$$P_U = 345 \times 10^3 \times 15 \times 15 = 77625\ \mathrm{kN}$$

Furthermore, regarding total load of 30,000 kN, the safety factor is:

$$S.F = \frac{P_u}{P_a} = {}^{77625}/_{30000} = 2.5 \qquad (27)$$

The obtained safety factor for shallow foundation is favorable. Shallow foundation analysis program is used so as to analyze and determine the settlement in shallow foundation with characteristics of mentioned soil. The settlement in the center of shallow foundation is 12.1 cm which is greater than the allowable settlement.

Design of Pile Group through Conventional Method

The problem of piled raft with dimension of 15×15, thickness of 1m, and piles with diameter and length of 1 and 10 m respectively, is analyzed. The number of piles is seven piles in seven rows. Besides, normal load equal to 30,000 KN is distributed uniformly across the area of pile, whether the settlement in the center of pile cap is determined to be 4.12 cm by using pile group analysis program. As can been seen clearly, the value of settlement is by far less than the allowable settlement (7 cm) and this , in effect, shows that this method is not economical.

Design of Pile Group through New Method

Due to mentioned load, the settlement exceeds the allowable limit. Regarding the concept of reducing-settlement pile foundation, settlements can be limited within the allowable range by introducing a number of piles in center of shallow foundation. Table 5 presents different types of reducing produced settlements.

Evidently, it can be seen that piled raft dimension of 15×15, thickness of 1m, and 25 piles with diameter and length of 1 and 10 m respectively, can be used to design this foundation.

All of the models run by FLAC 3D program and the maximum settlement are presented in Table 5 and one of these models is illustrated in Figure 11.

Table 5. Settlement in center of pile cap for different types.

Different types to design by new method	PROGRAM	Shallow foundation with 1 pile	Shallow foundation with 5 pile	Shallow foundation with 9 pile	Shallow foundation with 25 pile
Maximum settlement (cm)	Current program	9.9	8.3	7.9	6.2
	FLAC3D	10.2	8.85	8.14	6.72

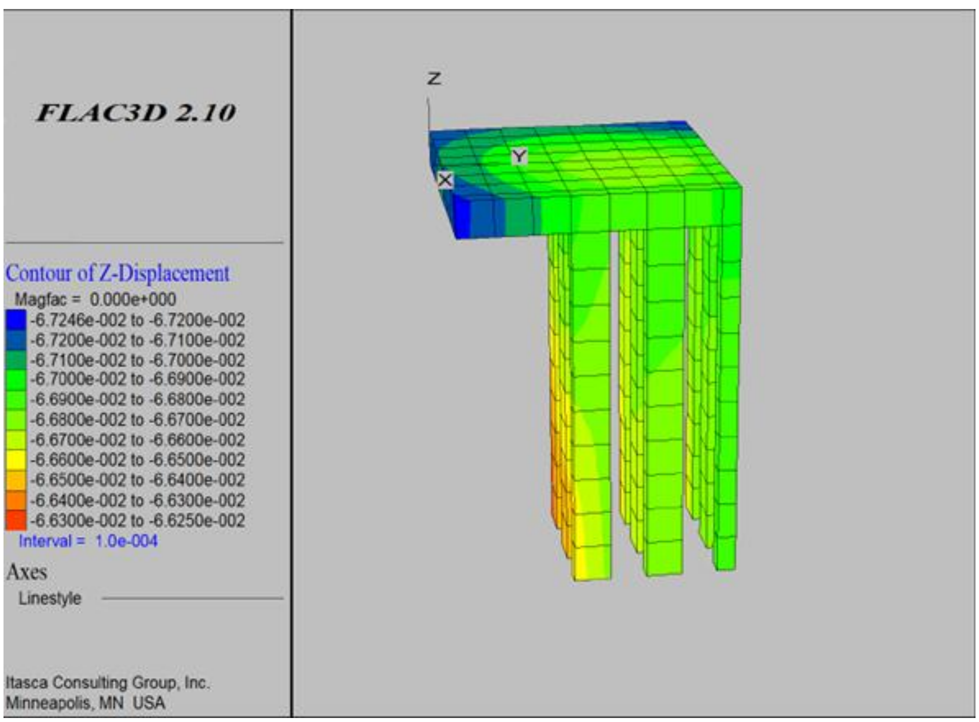

Fig. 10. Different concepts of settlement-load curve to design of pile group.

CONCLUSIONS

a. Modeling of soil and pile as springs leads to favorable results only in the event of considering interaction factors between springs.
b. The proposed algorithm and program have a high degree of accuracy relative to those analyses that use continuous medium mechanic and full numerical modeling.
c. The high speed of the proposed program is comparable with three-dimensional pile groups by commercial programs.
d. The design of pile group by new method (reducing-settlement pile foundation) is more economical than conventional methods.
e. Final conclusion: Employing the new method for pile group design (reducing-settlement pile foundation) requires using those programs considering load-bearing share of soil. The commercial programs based on continuous media mechanic for analyzing pile group are not employed because they are time-consuming. Analysis of pile group by considering bearing capacity of soil and pile can be conducted by the proposed algorithm and program, and practical designs with new concepts can be developed.

REFERENCES

Akin, J.E. (1988). *Finite element analysis for undergraduate*, Academic Press, London.

Badinlo, B.(2006). "Analysis of mat foundation on pile and soil and comparison of conventional and modern viewpoints to design pile group", M.Sc. Thesis, College of Engineering, University of Tehran, Tehran, Iran.

Feleming, W.G.K., Weltman, A.J. and Randolph, M.F. (2008). *Piling Engineering*, John Wiley and *Sons, 120p, Surrey University Press, London, UK, 3rd edition*.

Ghorbani,A. (1997)."Nonlinear and linear analysis of interaction between pile foundation and soil and comparison of analysis methods", M.Sc. Thesis, School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran.

Hooper, J.A. (1973). "Observation on the behavior of a piled raft foundation in London clay", *Proceeding of Institution of Civil Engineers*, 55(2), 855-877.

Poulos H.G. and Davis, A.J. (2005). "Foundation design for the Emirates twin tower, Dubai", *Journal of Geotechnical*, 6(42), 716-730.

Poulos, H.G. (1989). "Pile behavior – Theory and application", *Geotechnique*, 39(3), 365-415.

Poulos, H.G. and Davis, E.H. (1980).*Pile foundation analysis and design*, John Wiley and Sons, 250p, New York.

Poulos, H.G. and Makarchian, M. (1996), "Simplified method for design of underpinning piles", *Geotechnical Engineering, ASCE*, 122(9), 745-751.

Poulos, H.G., Small, J.C., Ta, L.D., Sinha, J. and Chen, L. (1997). "Comparison of some methods for analysis of piled rafts", *Proceedings of 14th International Conference on Soil Mechanics and Foundation Engineering*, Humburg, Germany, Vol. 2, pp. 1119-1124.

SaeediAzizkandi, A. (2008), "Analysis of piled raft against vertical load", M.Sc. Thesis, College of Engineering, University of Tehran, Tehran, Iran.

Timoshenko, S.P. and Woinowsky-Krieger, S. (1959). *Theory of Plates and Shells*, McGraw-Hill, New York.

Tsytovich, N. A. (1963). *Mekhanika Gruntov (soil mechanics)*, Stroiizdat, 4th Edition, Moscow.

Vesic, A.S.(1961). "Beams on elastic sub grade and the winkler's hypothesis", *5th International Conference on Soil Mechanics and Foundation Engineering*, Paris, Vol. 1, pp. 845-50.