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Optimum Design of Piled Raft Foundations Using A Genetic Algorithm

유전자 알고이즘을 이용한 Piled Raft 기초의 최적설계

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요 지

본 연구에서는, 유전자 알고리즘을 이용한 piled raft 기초의 최적설계 기법을 제시하였다. 최적설계에 사용한 목적함수는 구조물의 사용한계에 해당하는 부등침하량과 piled raft 기초의 시공비용 차원에서의 말뚝과 raft의 총 중량으로 하였다. 유전자 알고리즘은 다윈의 적자생존의 법칙을 따르는 자연진화 법칙을 바탕으로 한 최적화 기법이다. 본 연구에서는 piled raft 기초의 해석방법으로 Clancy(1993)가 제시한 "hybrid" 해석방법을 사용하였으며, 유전자 알고리즘기법은 Goldberg(1989)가 제시한 단순 유전자 알고리즘(SGA)을 적용하였다. 또한 유전자 알고리즘을 이용한 최적설계기법의 유효성을 평가하기 위해 설계예제 및 매개변수변화연구를 통해 piled raft 기초시스템의 중요 설계인자들에 대한 분석을 수행하였다. 매개변수변화연구로부터 말뚝의 길이와 raft의 두께가 증가할수록 piled raft 기초시스템의 전체 중량은 일정한 값에 점차적으로 수렴하였으며, 지반의 강성, raft의 두께 말뚝의 길이 및 강성이 증가할수록 말뚝의 최적위치는 raft의 중앙에 집중되는 경향으로 나타났다.

Abstract

In this paper, a new approach using a genetic-based evolution algorithm without gradient requirement is proposed for the optimum design of piled raft foundations. An objective function considered is differential settlements based on a serviceability of structures and total weights of raft and piles based on a cost of structures. A genetic-based evolution algorithm is a search or an optimization technique based on nature selection. Successive generation evolves more fit individuals on the basis of the Darwinian survival of the fittest. In formulating the genetic algorithm (GA) - based optimum design procedure, the analysis of piled raft foundations is performed based on the 'hybrid' approach developed by Clancy (1993), and also a simple genetic algorithm proposed by the Goldberg (1989) is used. To verify the efficiency of the GA-based optimum design procedure, two design examples of the piled raft foundations (5×5 and 3×3 group piles) are analyzed. In addition using the proposed optimum design procedure, parametric studies are performed with an aim of examining the effects of relevant variables on the optimum design of piled raft foundations. It is found from the results of parametric studies that as both the pile length and the thickness of a raft increase, the optimized total weight gradually converges into a certain constant value. The optimized results further represent a distinct feature that the piles become clearly concentrated on the central part of rafts with increases of the soil stiffness around piled rafts, the pile length, the thickness of a raft, and the pile stiffness.

Keywords : Optimum design, Piled raft foundation, Genetic algorithm

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1. Introduction

Civil engineers frequently work with optimization problems, such as structural design, resource allocation, transportation routing, and so forth. Traditionally, most optimization problems have been solved using operations research(OR) techniques, such as mathematical programming that a lot of gradient information is required. In recent years, genetic-based evolution algorithms have become a popular method for solving optimization problems. While the traditional OR approach requires different algorithms in solving different mathematical programming problems, the genetic algorithm(GA) - based method can be used to various optimization problems using the same genetic algorithm. Only the fitness and constraint functions are modified for different mathematical programming problems. In this paper, a new approach using a genetic-based evolution algorithm without gradient requirement is proposed for the optimum design of piled raft foundations.

2. Genetic Algorithm

Genetic-based evolution algorithms were originally introduced by Holland (1975), and later refined by De Jong (1975), Goldberg (1989), and others. The algorithms imitate the evolutionary process with a particular focus on genetic mechanisms. The simple genetic algorithm approach (Goldberg, 1989) operates on a group of individuals, where each individual represents a solution, encoding all the design variables. As schematically shown in Fig. 1, the evolution of generations is carried out by applying the genetic operators, such as reproduction and selection, crossover, and mutation.

The advantages of applying a genetic algorithm (GA) to optimum designs of geotechnical structures include discrete design variables and open format for various constraint conditions. A GA dose not require an explicit relationship between the objective function and the constraints. Instead, the value of the objective function for a set of design variables is adjusted to reflect any violation of the constraints.

GA has several important features. First, GA's simplicity and directness of characters make the representation of design, which must be encoded in a chromosome, easy for a variety of domain problems. Second, the GA operators acting on a chromosome at random are actually applied to a set or population of design rather than a single design point. This enables GA to explore the search space from many different points, simultaneously, and find an optimum by a more global search strategy instead of a localized gradient search or hill-climbing approach. Third, the fact that no gradient information is required avoids the mathematical complexity of numerical optimization methods. Fourth, the inherent ability of GA in implicit parallel computing can reduce the length of time during the evolution process. Finally, the GA approach has demonstrated certain aspects of intelligence characterized by human beings. That is, it exploits best inheritance accumulated during the evolution in a way that efficiently trades off the need to explore new regions of the search space. Thus the GA approach has been considered as an alternative optimization tool for a wide variety of optimization problems.

3. Optimum Design of Piled Raft Foundations

The most popular optimization criterion in structural design is a cost. Typically, cost is a function of the total weight of structures. Two cases of objective functions are dealt with in this study. In the first case, an objective function and a fitness function in terms of differential

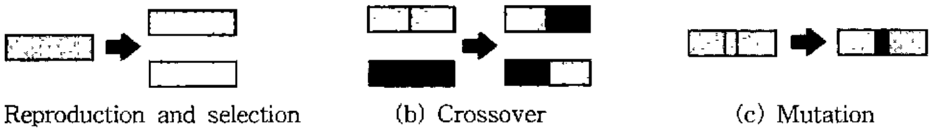

(a) Reproduction and selection (b) Crossover (c) Mutation

Fig. 1 Genetic operators

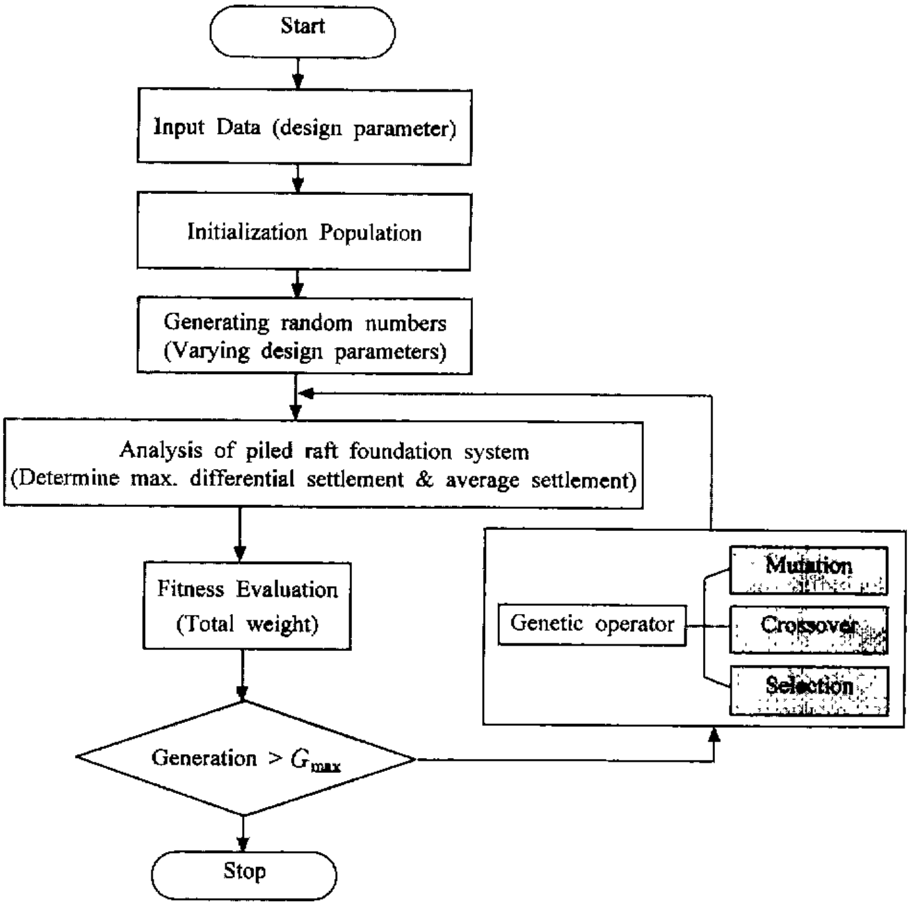


Fig. 2 Optimum design flowchart of piled raft foundations using a GA

settlements of piled raft foundations can be expressed as follows.

- Objective functions : $Q_{obj} = \min(S_{diff})$ (1)
- Fitness functions : $F = F_r + a$ (2)

where, F_r = raw fitness = $1/S_{diff}$, $a = const. = 0.5$

In the second case, an objective function and a fitness function in terms of total weights of piled raft foundations can also be expressed as follows.

- Objective functions :

$$Q_{obj} = \min(W_{total}) = \min(\sum_{i=1}^{n} W_{Pile_i} + W_{raft}) \quad (3)$$

- Fitness functions : $F = a + b \cdot F_r$ (4)

Where, F_r = raw fitness = $1/W_{total}$, a = const. = 0.5, $b = F_1 \cdot F_2$. Here values of F_1 and F_2 are assumed to be 1.0 if predicted differential settlements of piled raft foundations are less than the allowable differential settlement. Otherwise, values of F_1 and F_2 are assumed to be 0.0.

The optimum design flowchart of piled raft foundations using a genetic-based evolution algorithm is shown in Fig. 2, where the parameter Gmax in the stop criterion is the maximum number of generations allowed. In general, the maximum number of generations is dependent on the degree of difficulty of optimization problem. In addition, the piled raft foundations are analyzed based on the hybrid approach (Clancy, 1993).

A GA operates on a population of design variable sets. Each design variable set defining a potential solution is called a string. Each string is made up of a series of characters, typically binary numbers, representing the values of the discrete design variables for a particular solution. The fitness of each string is a measurement of performance of the design variables as defined by the objective function and the constraints.

Most genetic algorithms are variations of the simple genetic algorithm (SGA) proposed by Goldberg (1989). Goldbergs SGA consists of three basic genetic operators: reproduction, crossover, and mutation. The reproduction operation in the SGA is the basic engine of Darwinian natural selection and survival of the fittest. The crossover operation creates variations in the solution population by producing new solution strings that consists of parts taken from selected parent solution strings. The mutation operation introduces random changes in the solution population.

In this study, the initial population is created randomly. The most commonly used binary coding method is adopted. For example, two strings of randomly chosen 63 bits (0s and 1s) including design parameters are considered as follows.

0010110 | 1000101 | 1010011 | 0101101 | 0110101
| 1010110 | 0010101 | 0101011 | 1011101
1011011 | 0101110 | 1011100 | 0111001 | 0000101
| 1011110 | 0101011 | 0101110 | 1010111

These string sets are randomly expressed covering various radius of 9-piles ranging from 0.15m to 0.75m. The degree of accuracy between string sets is determined as follows.

$$\Delta r = \frac{b-a}{2^m} = \frac{0.75-0.15}{2^7} = 0.047\mathrm{m}$$

Where, a = minimum values of design parameters, b = maximum values of design parameters, and m = required bits for design parameters. The mapping from a binary string to a real number for the design parameter r1, is expressed as follows.

$$\begin{aligned} 0010110 &= decimal(r_1) \times \frac{b-a}{2^7-1} + a \\ &= 22 \times \frac{(0.75-0.15)}{(2^7-1)} + 0.15 = 0.253937\,m \end{aligned}$$

In the above process, each binary code is changed into the real code as follows.

25.39 | 47.60 | 54.21 | 36.25 | 40.04 | 55.63 | 24.92 | 35.31 | 58.94
57.99 | 36.73 | 58.46 | 41.93 | 17.36 | 59.41 | 25.39 | 36.73 | 56.10

The above string sets for design parameters are further randomly generated to new string sets throughout genetic operations of selection, crossover, and mutation.

4. Determination of Values of Control Parameters

Important control parameters of the GA are population size, probability of crossover and probability of mutation. Effects of three control parameters on the running time are analyzed and the results are shown in Fig. 3. Input parameters used in this analysis are summarized in Table 1.

Comprehensive analysis of the results in Fig. 3 indicates that the minimum running time required is achieved at values of 60(population size), 0.6(crossover rate), and 0.01(mutation rate).

5. Design Examples

To verify the efficiency of the proposed GA-based optimum design procedure, two examples of the piled raft foundations are designed. Design example #1 (5×5 piles in a group) focuses on an optimization of pile location satisfying the conditions that both total settlement and

Table 1. Input parameters used for determining efficient values of the control parameters

Pile		Square raft		Soil	
Pile number, n	2	Length, L & width, B	15.0m	Young's modulus, E_s	6.9GPa
Length, L_p	13.0m	Young's modulus, E_r	35.0GPa	Poisson's ratio, ν_s	0.4
Unit weight, γ_p	23.5kN/m^3	Unit weight, γ_p	23.5kN/m^3	Depth, h	Deep
Young's modulus, E_p	35.0GPa	Poisson's ratio, ν_r	0.16		

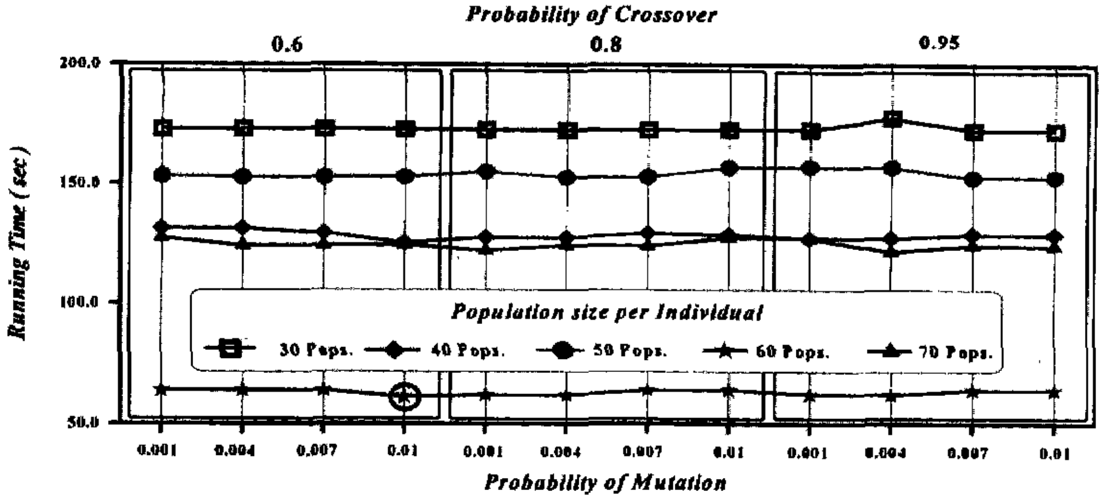
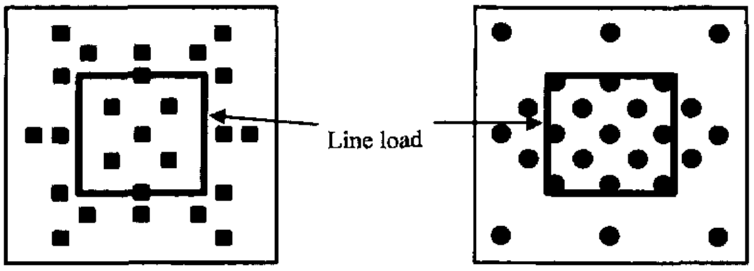


Fig. 3 Relationship of running time and the control parameters



(a) without interaction effects

(b) with interaction effects

Fig. 4 Optimized pile locations for design example #1

Table 2. Input parameters used for design example #1

Pile		Square raft		Soil	
Pile number n	25	Length, L & width, B	20.0m	Young's modulus, E_s	6.9GPa
Length, L_p	8.0m	Thickness, t_r	1.0m	Poisson's ratio, ν_s	0.4
Diameter, D_p	0.4m	Young's modulus. E_r	20.6GPa	Depth, h	Deep
Young's modulus, E_p	20.6GPa	Poisson's ratio, ν_r	0.2	Line load	0.17MN/m

Table 3. Input parameters used for design example #2

Pile		Square raft		Soil	
Pile number n	9	Length, L & width, B	13.0m	Young's modulus, E_s	35MPa
Length, L_p	15.0m	Thickness, t_r	0.8m	Poisson's ratio, ν_s	0.5
Unit weight, γ_r	23.5kN/m	Unit weight, γ_r	23.5kN/m	Depth, h	Deep
Young's modulus. E_p	35GPa	Young's modulus, E_r	35GPa		

differential settlement are the minimum. Input parameters used for the design example #1 are summarized in Table 2.

In processing the design, the diameter of a pile and the thickness of a raft are considered as fixed parameters, whereas the pile location is considered as a free parameter. The optimized pile locations in x-y plane with and without interaction effects are shown in Fig. 4. Analyzing the results of Fig. 4, it is concluded that the optimized pile locations are significantly influenced by interaction effects between pile-soil-pile, raft-soil-raft, and raft-soil-pile, resulting in a concentration trend to the central part of rafts. This trend

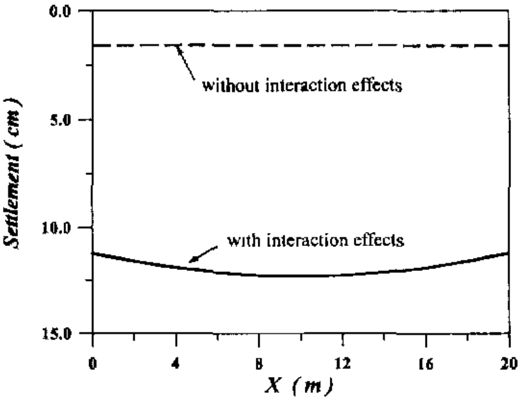


Fig. 5 Predicted settlements after optimization

is mainly attributed to the fact that as shown in Fig. 5, greater settlements are expected to occur at the central part of a raft compared to those expected at the edges. Design example #2 (3 × 3 piles in a group) is concerned with an optimization to minimize total weights of piled raft foundations. In this example, free variables are assumed to be the pile location and the pile radius, whereas the thickness of a raft is assumed to be a fixed variable. Input parameters used for the design example #2 are summarized in Table 3.

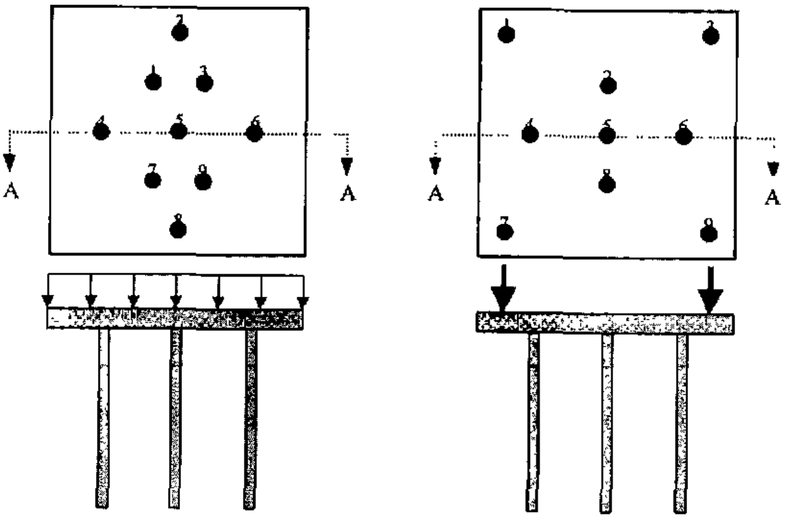
Fig. 6 shows the optimized results for two cases. Case I represents the optimized result under the condition that a surcharge of 118kPa is uniformly applied at the upper part of a raft, whereas Case II represents the optimized result under a concentrated load of 9MN applied at the corners of a raft. The radius of each pile for both cases is evaluated after the optimization process is done. A general trend similar to the design example #1 that the optimized piles are concentrated on the central parts of rafts is observed.

Table 4. Radius of each pile after optimization

Item	Radius of piles(m)			Tatal weight (MN)
Case I	① 56 ② 44 ③ 56	④ 15 ⑤ 75 ⑥ 15	⑦ 56 ⑧ 44 ⑨ 56	5.735
Case II	① 38 ② 15 ③ 38	④ 15 ⑤ 16 ⑥ 15	⑦ 38 ⑧ 26 ⑨ 38	4.461

6. Parametric Studies

Using the proposed GA-based optimum design procedure, parametric studies are performed with an aim of examining the effects of relevant variables on the design of piled raft foundations. The condition that a surcharge of 118kPa is uniformly applied at the upper part of a raft is considered in the present parametric studies, and values of input parameters are basically the same as those previously summarized in Table 1.



Section A-A
(a) Case I : Uniform loads

Section A-A
(b) Case II : Concentrated loads

Fig. 6 Optimal location of piles for design example #2

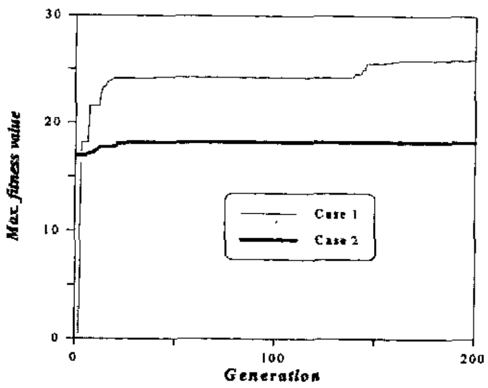


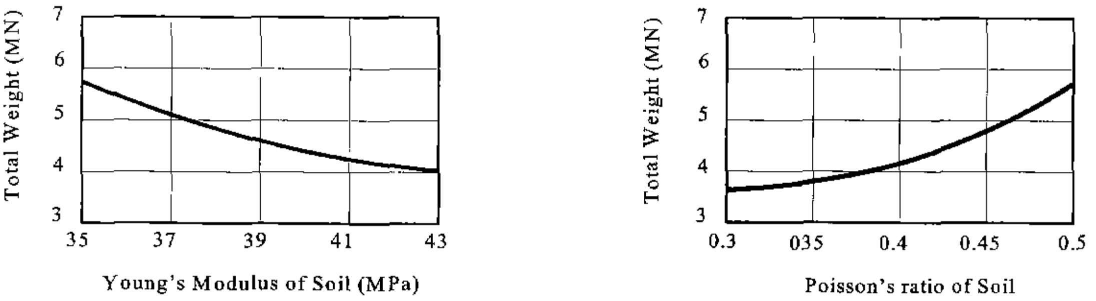
Fig. 7 Relationships of maximum fitness value to generation

6.1 Effects of Soil Stiffness and Geometry of Piled Raft Foundations

Detailed range of values of the Young's modulus of soil, the Poisson's ratio of soil, the pile length, and the thickness of raft, are summarized in Table 5.

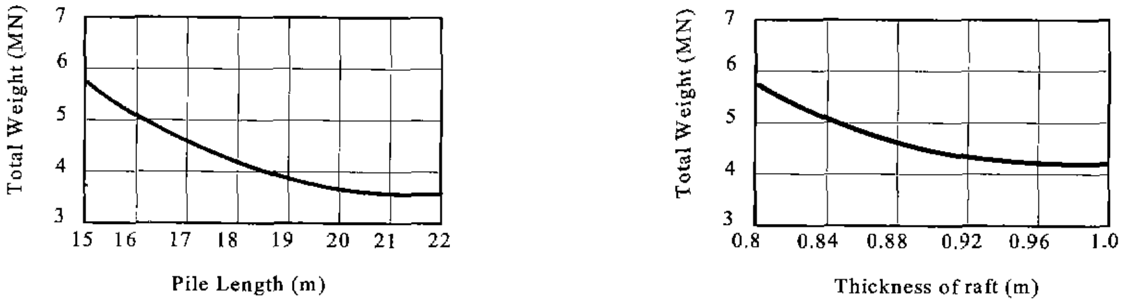
Variations of the optimized total weights of piled raft foundations with different values of the Young's modulus of soil, the Poisson's ratio of soil, the pile length, and the thickness of raft, are respectively presented in Fig. 8. Analyzing the results of Fig. 8, it is found that the optimized total weight gradually decreases as the soil stiffness around piled rafts increases. Another trend inferred from the results of Fig. 8 is that as both the pile length and the thickness of raft increase, the optimized total weight gradually converges into a certain constant value.

Pile locations of the optimized raft foundations with various values of the Young's modulus of soil, the Poisson's ratio of soil, the pile length, and the thickness of a raft, are further investigated. The optimized results are



(a) $\nu_s=0.5, L_p=15m,$ and $t_r=0.80m$

(b) $E_s=35MPa, L_p=15m,$ and $t_r=0.80m$



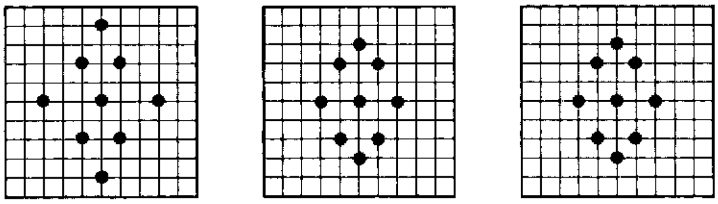
(c) $E_s=35MPa,\ \nu_s=0.5,$ and $t_r=15m$

(d) $E_s=35MPa,\ \nu_s=0.5,$ and $L_p=15m$

Fig. 8 Effect of relevant variables on the optimum design of piled raft foundation

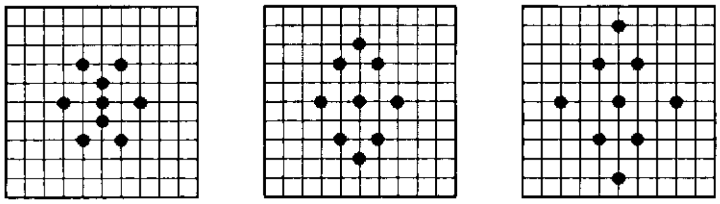
Table 5. Input parameters used for parametric studies

Pile		Square raft		Soil	
Pile number n	9	Lenght, L & width, B	13.0m	Young's modulus, E_s	35MPa
Lenght, L_p	15~22m	Thickness, t_r	0.8~1.0m	Poisson's ratio, ν_s	0.3~0.5
Unit weight, γ_p	23.5kN/m	Unit weight, γ_r	23.5kN/m	Depth, h	Deep
Young's modulus, E_p	35GPa	Young's modulus, E_r	35GPa		



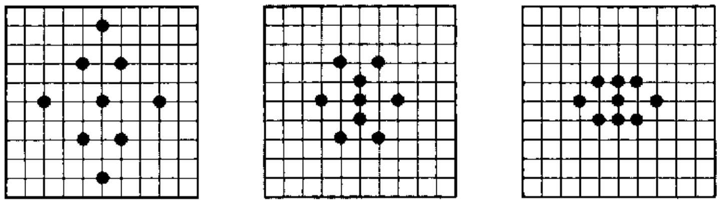
$E_s = 35MPa$ $E_s = 40MPa$ $E_s = 43MPa$

(*a*) $\nu_s = 0.5$, $L_p = 15m$, and $t_r = 0.80m$



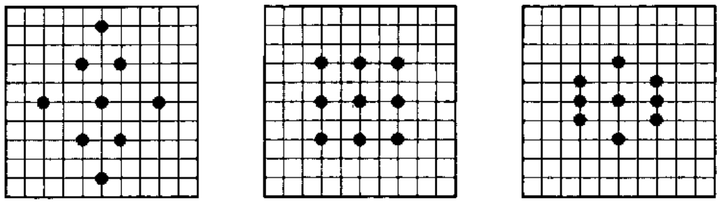
$\nu_s = 0.3$ $\nu_s = 0.4$ $\nu_s = 0.5$

(*b*) $E_s = 35MPa$, $L_p = 15m$, and $t_r = 0.80m$



$L_p = 15m$ $L_p = 20m$ $L_p = 22m$

(*c*) $E_s = 35MPa$, $\nu_s = 0.5$, and $t_r = 0.80m$



$t_r = 0.80m$ $t_r = 0.85m$ $t_r = 0.90m$

(*d*) $E_s = 35MPa$, $\nu_s = 0.5$, and $L_p = 15m$

Fig. 9 Optimized pile locations

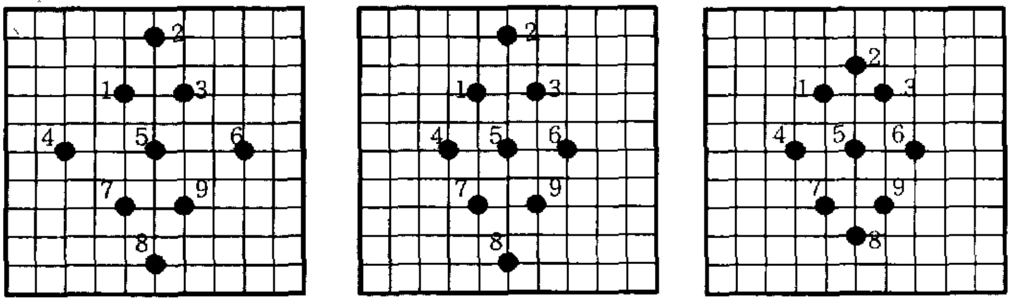
Table 6. Radius of each pile after optimization

Item	Concrete Pile						PHC Pile						Steel Pile					
Radius of pile (cm)	①	56	④	15	⑦	56	①	61	④	52	⑦	61	①	39	④	73	⑦	39
	②	44	⑤	75	⑧	44	②	15	⑤	36	⑧	15	②	16	⑤	16	⑧	16
	③	56	⑥	15	⑨	56	③	61	⑥	52	⑨	61	③	39	⑥	73	⑨	39
Young's modulus of pile (GPa)	35						44						200					
Total weight (MN)	5.735						5.730						5.530					

illustrated in Fig. 9, representing a distinct feature that the piles become clearly concentrated on the central part of rafts with increases of the soil stiffness around piled rafts, the pile length, and the thickness of a raft.

6.2 Effect of Pile Stiffness

Optimized total weights of the piled raft foundations with different values of the Young's modulus of pile are summarized in Table 6. Analyzing the result of Table 6, it



(a) Concrete Pile (b) PHC Pile (c) Steel Pile

Fig. 10 Optimized pile locations

is found that the optimized total weight gradually decreases as the pile stiffness increases.

Detailed pile locations of the optimized raft foundations are illustrated in Fig. 10, representing a distinct feature that the piles become clearly concentrated on the central part of rafts with an increase of the pile stiffness.

7. Constructions

In this paper, a new approach using a genetic-based evolution algorithm without gradient requirement is proposed for the optimum design of piled raft foundations. An objective function considered is differential settlements based on a serviceability of structures and total weights of raft and piles based on a cost of structures. In formulating the genetic algorithm-based optimum design procedure, the analysis of piled raft foundations is performed based on the 'hybrid' approach developed by Clancy(1993), and a simple genetic algorithm proposed by the Goldberg(1989) is used. The proposed GA-based optimum design procedure also considers interaction effects between pile-soil-pile, raft-soil-raft, and raft-soil-pile.

To verify the efficiency of the GA-based optimum design procedure, two examples of the piled raft foundations (5×5 and 3×3 group piles) are designed. Analyzing the results, it is concluded that the optimized pile locations are significantly influenced by interaction effects, resulting in a concentration to the central part of rafts. This trend is mainly attributed to the fact that greater settlements are expected to occur at the central part of rafts compared to those expected at the edges. In addition using the proposed GA-based optimum design procedure, parametric studies are performed with an aim of examining the effects of relevant variables on the optimum design of piled raft foundations. It is found from the results of parametric studies that the optimized total weight gradually decreases as the soil stiffness around piled rafts and the pile stiffness increase. Another trend inferred from the results of parametric studies is that as both the pile length and the thickness of a raft increase, the optimized total weight gradually converges into a certain constant value. The optimized results further represent a distinct feature that the piles become clearly concentrated on the central part of rafts with increases of the soil stiffness around piled rafts, the pile length, the thickness of a raft, and the pile stiffness.

Acknowledgements

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