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Geotechnical Design Optimisation of pile groups based on Particle Swarm Optimisation Technique

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Abstract: **This research work presents a geotechnical design optimisation algorithm for pile groups based on particle swarm optimisation (*PSO*) technique. The main objective of the research is to develop a computer program for optimising the size and configuration of pile groups using PSO, while satisfying the Eurocode 7 geotechnical design criteria. PSO is a gradient-free bio-inspired search algorithm capable of achieving global optimum by virtue of its capacity to cover a wide area searching for the best solution. The PSO design optimisation of pile groups were began with the generation of particle population with each member representing a set of pile groups and must satisfy the EC7 design criteria. The objective function of the optimisation is to minimised construction cost. The design variables were: pile diameter (*D*), length (*L*), thickness of the pile cap (*TH*), pile spacing (*S*), number of piles (*N*). and the input into the work were soil sub-surface profile, and loads. Two types of piles (bored and driven) are considered in the design optimisation and the static axial loads of 500kN, 2000kN, 4000kN, 8000kN, and 16000kN are considered, and the design were carried out in accordance with Eurocode 7. Cohesive and cohesion-less materials with multilayer thickness are also considered. The results showed that both types of piles (bored and driven) satisfied load ratio condition in both cohesive and cohesion less soils. The results have also shown that particle swarm optimisation (*PSO*) based design code developed during this research has been able to obtain optimised parameters involved in the design of pile groups.**

Keywords: **Piles, Optimisation, Algorithms, Program.**

I. INTRODUCTION

Piles foundations are a kind of deep foundations formed by long, slender, columnar elements typically made from steel or reinforced concrete and sometimes timber. A foundation is described as deep when its depth is more than three times its breadth [1]. Pile foundations are mainly to transfer axial and lateral loads from superstructure, through weak, compressible strata or water onto stronger, more compact, less compressible and stiffer soil or rock [2]. They are used for large structures, and in situations where the subsurface materials are not suitable to prevent excessive settlement. Generally, piles are classified based on their load carrying ability as; end-bearing piles (where most of the friction is developed at the toe of the pile, bearing on a hard layer) or friction piles (where most of the pile-bearing capacity is developed by shear stresses along the sides of the pile, suitable when harder layers are too deep). Most piles use some end-bearing and some friction, in order to resist the action of loads.

A. Background to Eurocode7

Eurocode 7 part 1 (EN 1997-1) was released by the European committee for standardization (CEN) in November 2004 for publication as a national standard in 30 countries throughout the European Union and the European free trade association (EFTA). The British standards institution published this standard as Bs EN 1997-1 in December 2004.The design of pile foundations is the subject of section 7 of Eurocode 7 part 1, covering topics such as: limit states; actions and design situations, design methods and design considerations; pile load tests; axially loaded piles; transverse loaded piles; structural design of piles; and supervision of construction. Section 7 comprises 167 paragraphs of which 98 are principles (general statements and definitions that must be followed) and the remainder Application Rules (generally recognized rules that comply with the principles and satisfy their requirements). Principles are identified by their use of the verb "shall"; application rules employ such verbs as "may" and "should". Section 7 applies to end - bearing, friction, tension, and transversely, loaded piles installed by driving, jacking, screwing, and boring (with or without grouting). References to paragraphs in euro code 7 parts 1 are denoted by the symbol §. For brevity, part 1 of Eurocode 7 will subsequently mainly be referred to as EC7 [3].

II. METHODOLOGY

Optimisation is the process of searching for optimal value of a function. The optimal value can be a maximum value, a local extreme point or a global extreme point. A function can have only one optimum or many, depending on the type of function. There are many different search methods and different ways to categorise them. One way is to divide methods into local and global optimisation methods, aiming at finding either local or global optima.

A. Previous Optimisation Studies

One of the earliest attempts to optimise the section of pile group was made by [4], In his report he developed a computer program that optimised the variables and batter to reduce the cost of the pile foundation. The optimisation was divided into several parts. First the pile cap was divided into a grid where piles were placed at all grid points and then the optimal batter was calculated. When the optimal batter had been obtained a search for the optimal spacing was carried out. This was done by a series of deletion passes where the least or most loaded piles were removed. When a set number of piles had been removed the spacing was increased. The process was repeated until the least number of piles possible was found. This work was based on the Nelder-Mead simplex method for unconstrained optimization. He transformed the constrained variables from the pile group optimisation to unconstrained variables to use the Nelder-mead method which is said to be less time consuming than methods for constrained optimization. There are two examples of pile foundation optimization where only pile length is varied in order to minimize differential settlements of the pile cap. Chow and Thevendran [5], similarly [4] used a direct search method for unconstrained optimisation, transforming their variables from constrain to unconstrained, however, using a different method of transformation. The genetic algorithm has been used in different form to optimize pile groups. A hybrid genetic algorithm was used to minimise the material volume of the foundation by mainly varying the pile diameter [6], Liu, Wu [7] used an Automatic Grouping Genetic Algorithm to minimise the cost (2011). They varied the pile diameter and the layout of the pile group. The piles were divided into different modules where all the piles had the same characteristics. Another example of pile optimization was performed by[8]; who used recursive quadratic programming to minimize differential settlements in a pile raft foundation. However, more recently [9] Used a discrete Lagrange multiplier method to minimize the construction cost of a bridge foundation. Several of the authors mentioned by [5] have based their optimisation programs on the current design codes (Eurocode). This allows for a more complete, design tool, but limits the use of the program to this specific code. The program developed in this thesis project is based on Eurocode7 design.

B. Particle swarm optimisation

Inspired by the flocking and schooling patterns of birds and fish, particle swarm optimization (PSO) was invented by[10]. Originally these two started out developing computer software simulations of birds flocking around food sources, then later realized how well their algorithms worked on optimization problems. Particles swarm optimisation might sound complicated, but it's really a very simple algorithm. Over several iterations, a group of variables have their values adjusted closer to the number whose value is closest to the target at any given moment. Imagine a flock of birds circling over an area where they can smell a hidden source of foods. The one who is closest to the food chirps the loudest and the other birds swing around in his direction. If any of the other circling birds comes closer to the target than the first, it chirps louder and the other peers over towards him. This tightening pattern continues until one of the birds happens upon the food. It's an algorithm that's simple and easy to implement.

The algorithm keeps track of three global variables:

1. Target value or condition
2. Global best (gBest) value indication which particle's data is currently closest to the target.

3. Stopping value indicating when the algorithm should stop if the target is not found.

Each particle consists of:

a. Data representing a possible solution

b. A velocity value indicating how much the data can be changed

c. A personal best (PBest) value indicating the closest the particle's Data has come to the target.

The particles' data could be anything. In the flocking birds example above, the data would be the X, Y, Z coordinates of each bird. The individual coordinates of each birds would try to move closer to the coordinates (gBest). If the data is a pattern or sequence, then individual pieces of the data would be manipulated until the pattern matches the target pattern.

III. RESULTS AND DISCUSSIONS

This chapter explained the result obtained from optimisation of pile group parameters designed in accordance with the Eurocode 7. The information given were: piles type (bored and driven), sub – surface profile of the materials, static axial loads, as in the programme code attached in the appendix1

Subsurface Characterisation Based on Shear Strength Parameters (c and ϕ)

Here based on the results obtained and graphs plotted, both the types of piles satisfied the load ratio conditions in cohesive soils, which is an economical design.

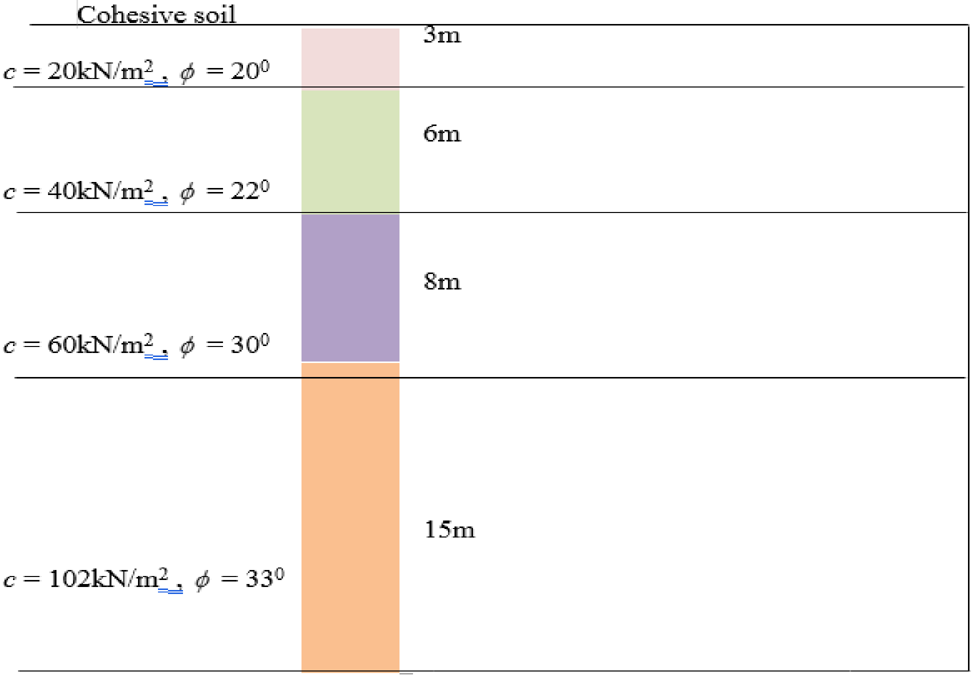

Figure1: Borehole log showing the properties of the soil

TABLE I: OPTIMISED DESIGN PARAMETERS FOR 500KN LOAD

Load (kN)	**Soil type**	**Pile type**	**Diameter D (m)**	**Length L (m)**	**Spacing S (m)**	**Pile cap thickness TH (m)**	**Number of piles N**
500	cohesive	Bored piles	0.45	12.2	0	0	1
		Driven piles	0.30	23.5	0	0	1

From Table1, and figure 1 and 2, the result shows that bored pile has a diameter of 0.45m and length of 12.2m while driven pile has a diameter of 0.30m and length of 23.5m which shows that the diameter of bored pile is half of the driven pile while in the case of driven the length is more than half of the bored pile but the number of piles remain the same and the graphs are both within the acceptable limits of load ratio conditions and normalised cost are also at optimum.

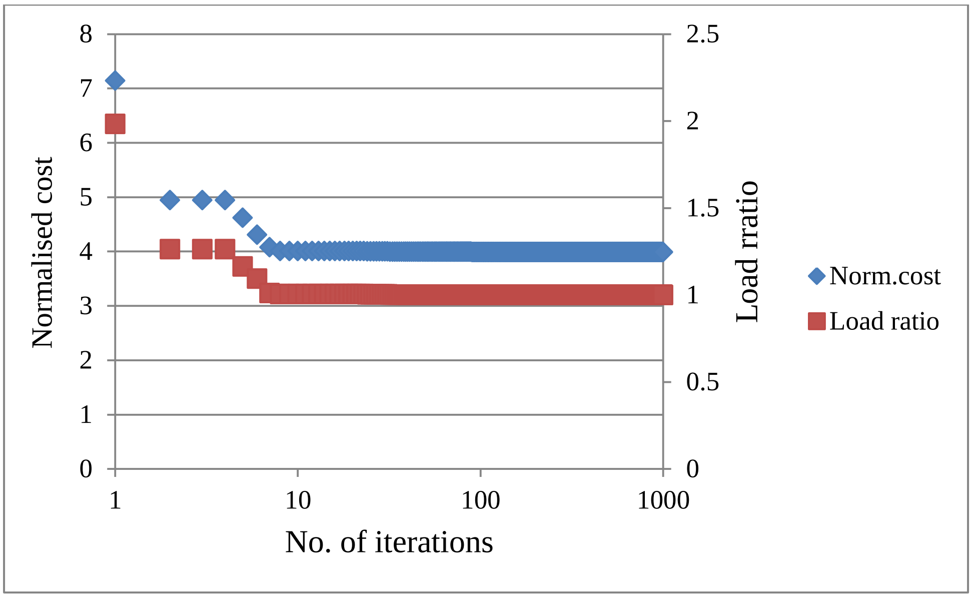

Figure 2: Normalised cost/Load ratio for 500kN static axial load (Bored piles)

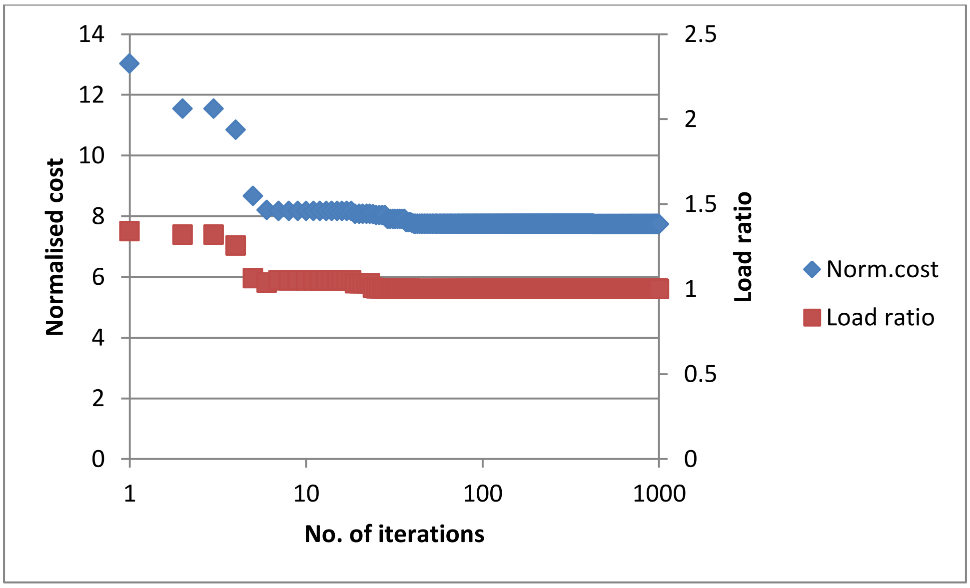

Figure 3: Normalised cost/Load ratio for 500kN static axial load (Bored piles)

TABLE II: OPTIMISED DESIGN VARIABLES FOR 2000KN LOAD

Load kN	Soil type	Pile type	Diameter D (M)	Length L (M)	Spacing S (M)	Pile cap thickness TH (M)	Number of piles N
2000	cohesive	Bored piles	0.60	27.0	0	0	1
		Driven piles	0.30	23.6	1.2	0.7	4

From Table 2, figure 4 and 5, the result shows that bored pile has a diameter of 0.60m length of 27m while driven pile has a diameter of 0.30m and length of 23.6m which shows that the diameter of the bored pile is twice that of driven while the length of the two piles shows little difference, with the four numbers of piles for the driven and single pile for the bored, and the graphs are both within the acceptable limits of load ratio conditions and normalised cost are also at optimum.

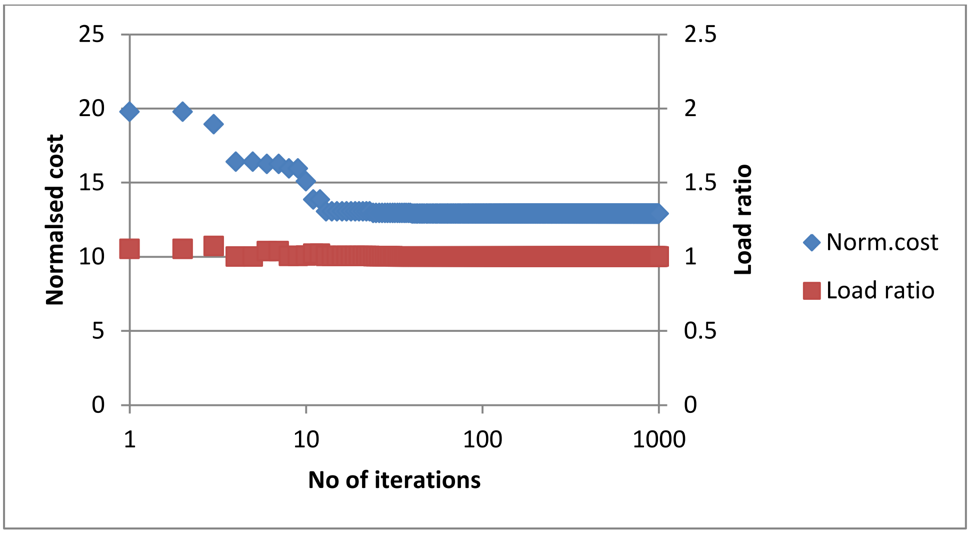

Figure 4: Normalised cost/Load ratio for 2000kN static axial load (Bored piles)

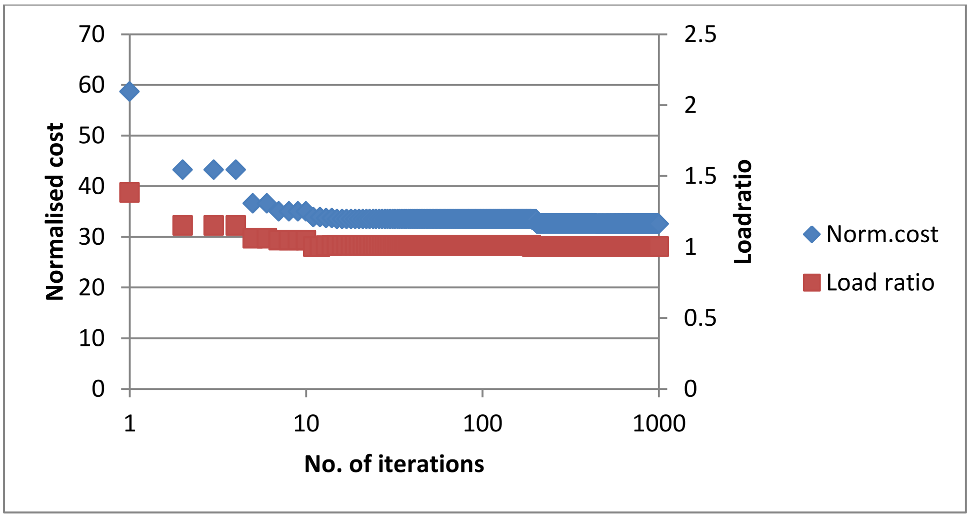

Figure 5: Normalised cost/Load ratio for 2000kN static axial load (Driven piles)

SUMMARY

Based on the sub- surface characterization of shear strength parameters and the static axial loads considered in the design, as shown in table 3 cohesive and cohesion less soils are all capable of withstanding the loads under bored and driven piles, and they all passed the load ratio condition of the design, and the normalized cost is at optimum. Pile groups placed in cohesive soils have collective strength which is considerably less than the summation of the individual pile strength which composes it. The strength of pile groups may be governed by its strength at block failure. This is when the soil fails along the perimeter of the groups, while pile groups in cohesion-less soils (piles driven in sand and gravels) compacts the soils between the piles. This compactive effect can make the bearing capacity of the group greater than the sum of the individual pile strength.

TABLE III: SUMMARY OF RESULTS

Layer thickness	**Soil type**	**Loads (kN)**	**PILE TYPE**									
Multi-layer	Cohesive		BORED					DRIVEN				
			L(m)	D(m)	S(m)	TH(m)	N	L(m)	D(m)	S(m)	TH(m)	N
		500	12.20	0.45	-	-	1	23.54	0.30	-	-	1
		2000	27.00	0.63	-	-	1	23.65	0.31	1.20	0.70	4

IV. CONCLUSION

From the results obtained, the conclusion of this research can be deduced as follows:

1. The load carrying capacity of piles and pile groups are successfully estimated based on the information obtained about the sub-surface soil profile, for safe and economic design.
2. The proposed PSO-based algorithm has successfully been optimised the parameters of the pile group design such as length, diameter, spacing, pile cap thickness, and number of piles, based on the provisions of EC7.
3. The computer program developed in this research has been successfully implemented in the geotechnical design optimisation of pile groups.

V. RECOMMENDATIONS

1. Driven piles are the most favoured for the works in cohesion-less soil due to load ratio satisfaction and compaction of the adjacent soil mass as a result, the bearing capacity of piles increased; while bored piles are suitable in cohesive soil due load ratio satisfaction and do not significantly disturb the surrounding soil or adjacent structures, and further research should be carry out on the piles to include lateral and dynamics loads to see the effect.
2. The partial factors suggested in EC7 for pile resistance are numerically much lower than have traditionally been used in the design of pile foundations. Therefore, code often gives economic design and less risk for failure or expensive remediation.
3. Bearing capacity estimation should be based on ground conditions and their variability across the site and the documented evidence of relevant pile performance in similar ground conditions should be compared.
4. More research should be conducted to estimate piles capacity based on pile loading test to see the effect when comparing the result with the laboratory and in-situ experimental based results.

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