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APPLICATION OF GENETIC ALGORITHMS TO STRUTTED SHEET PILE WALL DESIGN OPTIMIZATION

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Abstract. *Strutted sheet pile wall represents an economic commonly used solution for vertical or near vertical deep excavation, when open cuts with side slopes are not applicable. It is mainly used to minimize/ control ground deformations to ensure safety of adjacent structures. Thus, the strutted sheet pile wall design process should present elements with sufficient strength/ stiffness to resist the lateral earth pressure without losing the economic advantage. Although the choice of strut and wall configuration is very precise and sensitive process to optimize the design, it still depends on empirical formulas and designers' experience. Application of optimization to this process can bring out some scientific based design rules.*

In this research, a heuristic optimization technique, Genetic Algorithms, is applied to the strutted sheet pile wall design. The optimization process aims to minimize the construction cost expressed with elements dimensions considering both deformation and stress constraints for the ground soil and construction material. The Genetic Algorithms technique is combined with Finite Element Analysis to find the optimal values for the design variables (strut cross section and position and sheet pile wall thickness and embedded depth) for different soft soil types. Results can be used to draw a map for the design process.

1 INTRODUCTION

Development projects in urban congested areas such as transportation tunnels, underground parking garages, basements and utilities…etc. necessitate the use of the underground space and hence the use of side support systems to retain their deep excavations.

Generally, excavation support systems for deep excavations consist of two main components: a wall, and its supporting measures. Walls supporting deep excavations may be classified into the following three major categories according to the form of supporting measures provided for them: (1) Cantilevered wall (usually for relatively shallow excavation); (2) Strutted/braced wall; and (3) Tied-back or anchored wall.

Many factors affect the excavation-induced deformations such as: wall stiffness, stiffness of supporting measures, ground conditions, groundwater condition and control measures, excavation depth, construction sequences and workmanship. Strutted sheet pile wall represents an economic commonly used solution for vertical or near vertical deep excavation as it minimizes ground deformations to ensure safety of adjacent structures. Design optimization of strutted wall systems will have a significant impact on cost especially for infrastructure projects with deep excavation.

In 1981, Mana & Clough made few trials on the impact of one effective design parameter in an attempt to reach a better design for the strutted sheet pile wall [1]. They showed that increasing the stiffness of the strut/anchor/raker reduces the deformation 40% as shown in Figure 1.

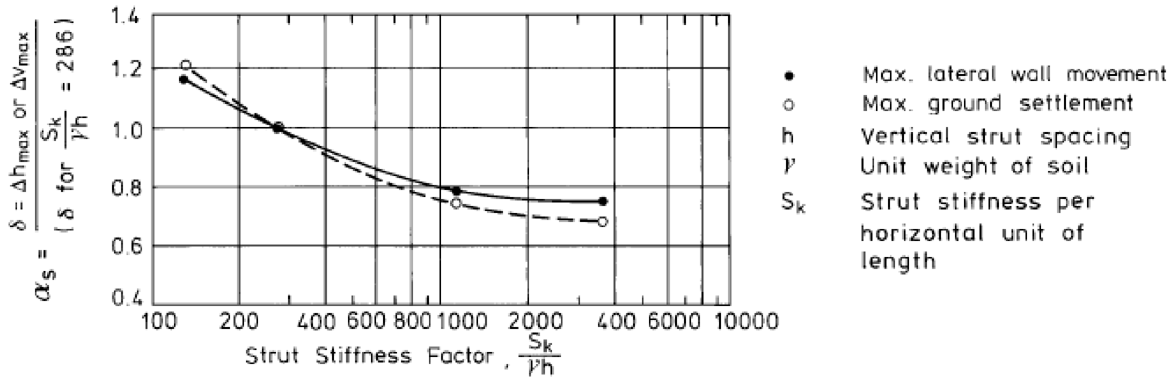

Figure 1. The effect of the strut stiffness on the maximum lateral deformation of the wall and the maximum settlement [1].

Recently, in 2012, Chowdhury, Deb, and Sengupta carried out a parametric study (16 design cases of diaphragm wall systems with different strut arrangements) to investigate the influence of different design parameters, such as strut stiffness, wall thickness, strut arrangement and the embedded depth of the wall on strut force, maximum moment developed in the wall, maximum lateral displacement of the wall, and maximum vertical displacement of ground surface. The parametric study was used to derive a design guideline to optimize the side support system. It was observed that, for a particular wall thickness and strut stiffness, different strut arrangements produced different results for maximum strut force, maximum moment, maximum horizontal wall displacement, and maximum vertical ground surface displacement [2].

A real optimization process cannot be performed for such problem through deterministic search methods. The calculus based analytical methods depend on the existence of mathematical formula and continues functions to express the studied problems, which are not available in this case. Application of enumerative search method shall consume a very long time to reach the optimal solution, regarding the large search space [3]. Thus, stochastic search methods shall be more efficient in such optimization problem. This research aims to demonstrate how a heuristic optimization technique, Genetic Algorithms, can be applied to reach an optimal or a quasi optimal solution with reasonable computation cost.

2 GENETIC ALGORITHMS

Genetic Algorithms (GA_s) are search and optimization procedures that are motivated by the principles of natural genetics and natural selection. They are also referred to as stochastic optimization techniques different from usual mathematical programming [4]. Being considered as stochastic methods, the GA_s do not need specific information to guide the search, and require only an evaluation of the objective function value for each decision variable set in order to proceed. They typically work with a coding of the decision variables, not with the decision variables themselves. They search simultaneously using a population of decision variable sets, not a single set of decision variables [5].

As in a biological system submitted to external constraints, the fittest members of the population are selected to survive and given better chances of reproducing and transmitting part of their genetic heritage to the next generation. A new population is then created by recombination of parental genes. It is expected that some members of this new population will have acquired the best characteristics of both parents and, being better adapted to the environmental conditions, will provide an improved solution to the considered problem. After it has replaced the original population, the new group is submitted to the same evaluation procedure, and later generates its own offsprings. The process is repeated many times, until elite members of a given generation share the same genetic heritage. These members, who are often quite different from their ancestors, possess genetic information that corresponds to the best solution to the optimization problem [6].

3 OPTIMIZATION PROBLEM DESCRIPTION

The optimization problem addressed herein is to find out the optimal wall embedded depth, sheet wall section and struts number, section and positions those lead to pre-specified safe lateral deformation during excavation and acceptable induced stresses in soil and structural elements to have minimum system cost. Figure 2 shows a half section for the structural system and geometrical variables considered.

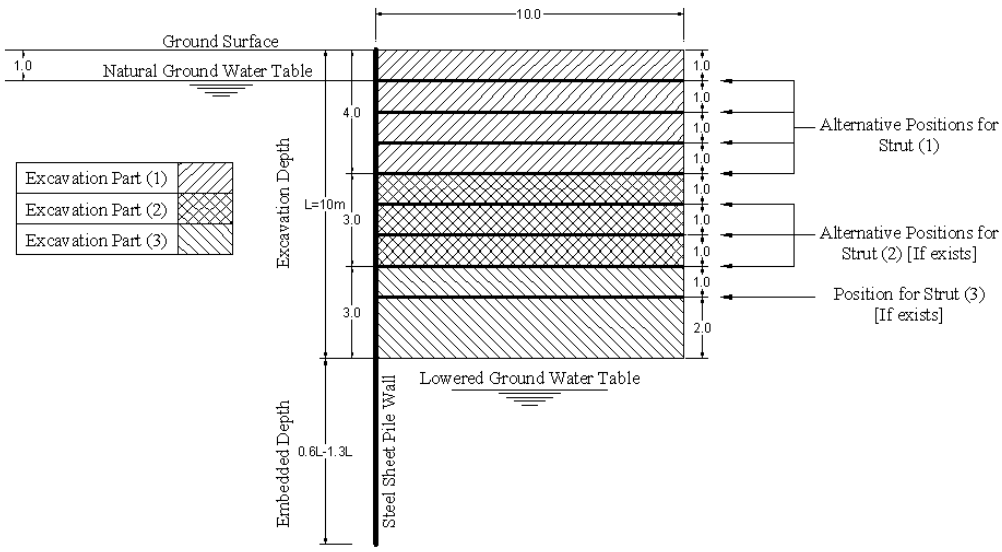

Figure 2: Problem layout and geometrical variables.

Hence, the objective function can be stated as:

$$\text{find } X \in R_k \text{ to}$$
$$\text{minimize f (X)}$$
$$\text{subject to } g_i\text{ (X)} \leq 0,\ i = 1, 2, \ldots, n \text{ and}$$
$$X_j^L \leq X \leq X_j^U, \qquad j = 1, 2, \ldots\ldots\ldots, k$$

where X is the vector of design variables; f (X) is the objective function; $g_i(X)$ is the performance constraints; and X_j^L and X_j^U refer to the lower and upper bounds on the design variables respectively. The objective function here is the weight of the system and can be expressed as:

$$\min W = \gamma_s (L_w S_w + L_s S_s N_s) \qquad (1)$$

where γ_s is steel density, L_w is the sheet wall total length, S_w is the sheet wall cross-sectional area, L_s is the strut length, S_s is the strut cross-sectional area and N_s is the struts number.

3.1 Design Variables

Six design variables are considered in this optimization problem:

1) Sheet pile wall section: the section is selected from 8 different alternatives shown in Table 1 [7].
2) Sheet pile wall embedded depth: a range from 0.6 L to 1.3 L, where L is the excavation depth, with 0.1 L step is examined.
3) Strut section: 8 different pipes from Egyptian standard steel sections, shown in Table 2, are selected.
4) Upper strut position: 4 different alternative positions for upper strut are considered; at 1, 2, 3 or 4 m depth from ground surface.
5) Middle strut existence/position: this one has an optional existence with 3 alternative positions; at 5, 6 or 7 m from ground surface.
6) Lower strut existence: it has an optional existence at a certain position; 8 m from ground surface. So, it is a yes/no variable.

Section No.	Section Name	Width (mm)	Height (mm)	Back thickness (mm)	Web thickness (mm)	Inertia (cm^4/m)
1	Larssen 600	600	150	10.0	9.9	4050
2	Larssen 601	600	310	8.0	6.8	12245
3	Larssen 602	600	310	8.7	8.4	13640
4	Larssen 603	600	310	10.2	8.5	19375
5	Larssen 604	600	380	10.5	9.2	31675
6	Larssen 605	600	420	13.0	9.2	43890
7	Larssen 606	600	435	14.9	9.4	55900
8	Larssen 607	600	452	19.5	10.8	73900

Table 1: Alternative sections for sheet pile wall.

Section No.	Pipe No.	Diameter (mm)	Thickness (mm)	Area (cm^2)	Radius of gyration (cm)
1	325	325	8	79.7	11.2
2	325	325	10	99.0	11.1
3	368	368	8	90.5	12.7
4	368	368	10	112.0	12.7
5	419	419	10	128.0	14.5
6	419	419	12	153.0	14.4
7	529	529	9	147.0	18.4
8	529	529	10	163.0	18.4

Table 2: Alternative sections for struts pipes.

3.2 Constraints

The performance constraints include concern for two types of safety conditions:

1) Stress condition: the induced stresses in soil, sheet wall and struts, including buckling effect in struts, should be within allowable limits.

$$g_{1i} = |\sigma_i| - \sigma_{all} \leq 0, \qquad i = 1, 2, ...m \tag{2}$$

2) Deformation condition: lateral displacements in sheet wall during excavation should not exceed the pre-specified limit (0.005 L = 5 cm).

$$g_{2i} = |\Delta_i| - \Delta_{all} \leq 0, \qquad i = 1, 2, ...m \tag{3}$$

4 NUMERICAL MODELING

In this paper, conventional numerical model with plane-strain analysis is used. Figure 3 shows the finite elements mesh used for simulation with close views for excavation area before and after excavation.

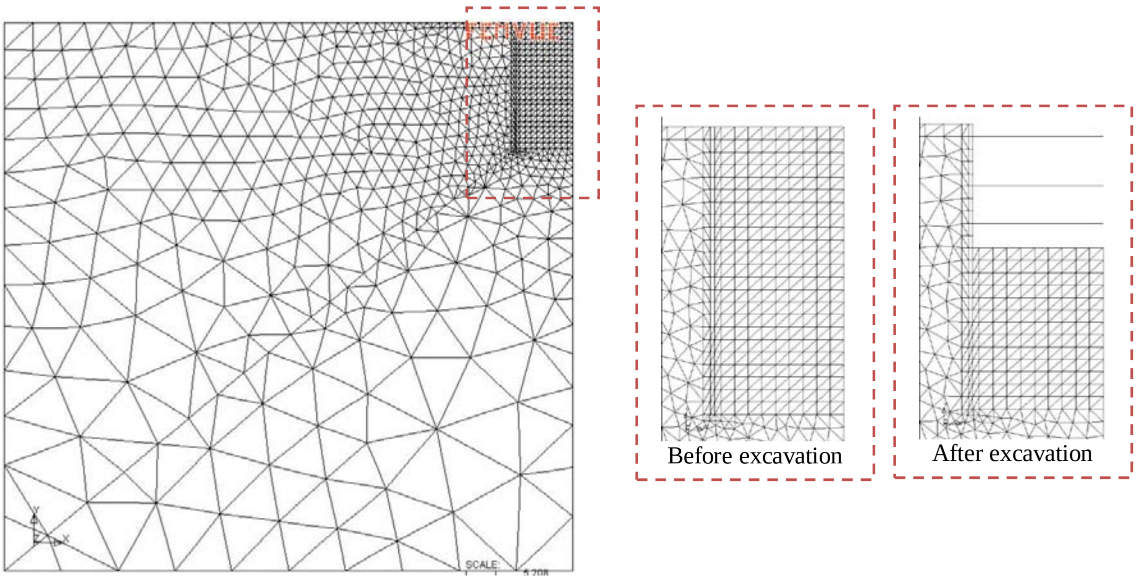

Figure 3: Finite elements simulation mesh.

For the modeling process in the Finite Element program, FINAL package [8], the soil media is modeled using six-node linearly varying strain triangular finite elements (L.S.T), the sheet pile wall is presented by six-node beam elements (Beam6) and the strut is modeled by two-node link member (Beam2). Ground water is presented with its net lateral load. A half-section mesh is used in the analysis to reduce computation time. Sufficient mesh depth and width, to model soil infinite body, are used. For boundary condition, vertical and horizontal movements are prevented at the bottom of the model while only the horizontal movements are prevented at both sides.

4.1 Geotechnical Parameters

Two different soil types are examined, in two different models, in order to check the impact of soil parameter on optimal values. Characteristic and mechanical properties for these soil types are given in Tables 3 and 4.

Density	19 kN/m^3
Elastic Modulus	20 MPa
Poisson Ratio	0.3
Angle of Internal Friction	35 ^{o}
Cohesive Strength	0 kPa

Table 3: Mechanical properties for sandy soil.

Density	20 kN/m^3
Elastic Modulus	15 MPa
Poisson Ratio	0.45
Angle of Internal Friction	0 ^{o}
Cohesive Strength	50 kPa

Table 4: Mechanical properties for clayey soil.

5 COMPUTATION PROCEDURE

5.1 Enumerative Search Process

The main target, for current research, is to check the feasibility and efficiency of GA_s application in the studied geotechnical problem. So, an enumerative search process was performed to investigate all possible solutions to find the global optimal solution and the associated design parameters. For each soil type, the search space was divided to four equal parts. Four moderate speed PCs run continuously for about 48 hours to finish this automated search process. Tables 5 and 6 summarize the search results.

	Sandy Soil	Clayey Soil
Number of safe solutions	10629	11206
Number of unsafe solutions	5755	5178
Maximum safe weight (ton/m)	6.472	6.472
Minimum safe weight [optimal value] (ton/m)	1.872	1.759

Table 5: Enumerative search general statistics.

	Sandy Soil	Clayey Soil
Sheet pile wall section	Larssen 602	Larssen 601
Sheet pile wall embedded depth	0.6 L = 6 m	0.6 L = 6 m
Strut section	Pipe 325 (section 1)	Pipe 325 (section 1)
Upper strut position	4 m from ground surface	4 m from ground surface
Middle strut existence/position	None	None
Lower strut existence	None	None

Table 6: Global optimal solution.

5.2 Optimization Process

According to the assumed alternatives for every variable, the total number of possible solutions (chromosomes) = 8*8*8*4*4*2 = 16384, for each soil. An initial population of 8 chromosomes is considered. Each individual is sent to the FINAL package to check the stresses in structural elements and lateral displacement and compare them with the allowable values. Unsafe solutions get penalty function; their evaluation value (system total weight) is multiplied by 10. Then, all solutions are encoded to binary form to facilitate the application of mating operators. Genetic Algorithm's mating operators are crossover and mutation. Each two solutions are mated together to produce two children solutions. Like their parents, produced solutions have to be checked. Unsafe produced solutions, also, get the penalty function. Both parents and children solutions are collected in one pool and sorted in an ascending order. The last 8 solutions are discarded and the first 8 solutions form the parents' population for the next generation. Processing optimization operators and repeating them through generated population leads to convergence toward global optimum.

The termination criteria is defined with limited number of generations; 200 generations. During these generations production, the GA_s computer program explores about 1600 solution which is less than 10% of the search space. Difficulty of having optimal or quasi optimal solution increases as convergence rate increases. Thus, the mutation probability is increased from 20% in the first 100 generations to 40% in the second 100 generations. Figure 4 shows the structural overall weight progression through generations for different analysis times.

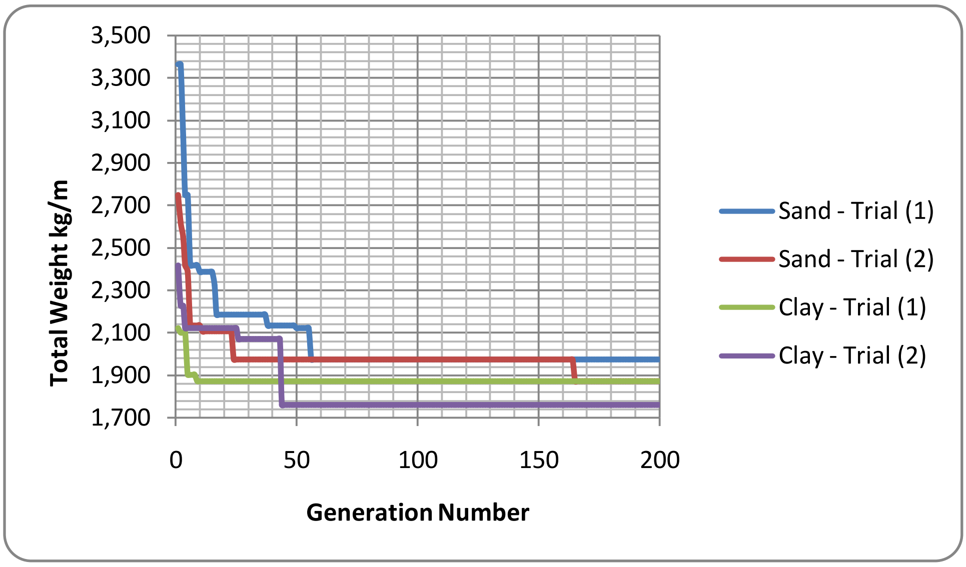

Figure 4: Overall system weight progression through generations.

In different analysis times, the program managed to find the global optimal or a quasi optimal solution (less than 7% higher than optimal system weight) before termination. The analysis consumes 18 hours on a moderate computer specifications (Core2 Duo processor, 2.0 GHz speed and 2GB RAM).

6 CONCLUSIONS

- GA_s have proven to be successful in the presented optimization problem.
- Despite the large search space, the program managed to reach the optimal or near optimal solution in reasonable time and iterations number.
- Increasing the mutation probability did not help enhancing the progression.
- Repeating the application for different soil and geometric conditions can draw a map for this design process.

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