Cost and safety optimization in “Berlin” type retaining walls

Abstract: Studies for earth retaining wall structures provide engineers with the values for the response of design characteristics which represents the stability and the required budget for the completion of a project. Fundamental theories guide engineers to combinations of design variables values. These values have a direct relation to the responses of the earth retaining wall structure. The requirement of this analysis is that there is no proven technique which ensures the best combination of design variables for the simultaneous optimization of safety factor and overall cost of a project. This paper presents an integration of the desirability analysis which provides the multivariate optimization with the performance of few experimental runs based on statistical tools and finite elements methodology. The methodology provides a 24% higher safety factor and 50% lower overall cost comparing to the results of an experienced foundation engineering company.

Keywords: Multi-response optimization; Earth Retaining Wall Structure; Safety Factor; Overall Cost

1. Introduction

The combination of the best quality to the lowest possible price is the required for a product, process or service in order to be credible. Earth retaining wall structures are construction that supports the adjacent earth masses and properties and need to be stable and financial profitable. The excavation works, the steel section reinforcement the anchoring details and the required man-hours for the completion of a project are parameters that needs to be carefully examined for a safe and simultaneously economical construction.

The procedure followed for the safety factor and overall calculation is accomplished with combinations of design characteristics which are responsible for the response of this system. Proven techniques for the simultaneous optimization of those two design characteristics do not exist and engineers provide an accepted but not statistical verified solution for their calculations.

The presented methodology presents an innovated integration of the desirability analysis to a “Berlin” type earth retaining wall structure, by examining the design variables for the simultaneous optimization of the design characteristics of the project.

2. State of the art

Optimization methodologies are applicable to a wide range of projects. The requirement for the presented article is the implementation of the integrated desirability analysis to fit to the majority of case studies. After an extended analysis of the projects assigned to a foundation engineering company, the most common type of an earth retaining “Berlin” wall type structure was projects with a single anchoring row.

Moreover, another issue concerning engineers responsible for the design of these earth retaining structures is the type of the used steel section. The options for the vertical steel sections are double mirrored UPN or single HEB steel sections. Thus, the quality methodology implemented needed to go a step further from the current analyzed methodologies.

In concluding the presented methodology offers a tool for engineers that apply to the majority of earth retaining wall structures projects which examines not only a wide range of design variables values but also the type of steel section used.

3. Methodology Development

Desirability analysis, along with genetic algorithms, fuzzy logic routines and neural networks are methodologies from the evolution of the Design of Experiments (DOE) methodology (Montgomery, 2008).

The assignment of weights that reflect the importance of the design variables was achieved via the desirability function for simultaneous multi response optimization (Chen, 2013), while the overall desirability of the solution depends on the levels of the experimental factor we used a desirability function (Harrington,1965 and Derringer and Suich, 1980).

The optimization of the most important design characteristics in an earth retaining structure is an issue which has a smooth evolution over the years. The first approach for this optimization was the quality improvement of safety factor in construction design with the implementation of Taguchi analysis in a six sigma project (Telis et.al 2008a). The methodology was upgraded with the addition of more than factors with a multivariate optimization via the desirability analysis analysis (Telis et.al 2008b, 2011). The critical analysis of this approach showed (a) that the examined methodology could not be implemented to the variety of projects and (b) that the design variables and their range values could be upgraded for the improvement of the methodology.

4. Desirability Analysis

The quality tool used in the presented paper is an integration of the desirability analysis. Desirability analysis examines the contribution of each design variable to safety and cost response. This is performed with the calculation of the overall or composite desirability *D* the following equation:

$$D = \left(F_1(y)^{W_1 I_1} \cdot F_2(y)^{W_2 I_2} \cdots F_n(y)^{W_n I_n}\right)^{1/(I_1+I_S+\cdots+I_N)} \quad (1)$$

where *Wi* and *Ii* are the weight and importance for the response *i (i=1,2,…n)* and *fi(y)* is the function that describes the approach method of the *y* response. The two design characteristics were ranked with the same importance, while their weights were relative to their response graph from the preliminary runs performed.

This methodology was applied to a real life single anchoring row case study located to the center of Athens.

This project was assigned to a foundation engineering company in Greece, where the available data of the case study are:

- 18,00m length and 7,00m depth of the earth retained surface
- The site is adjacent to a 2-floor building without underground basement or parking
- The planning is for a 6-floor building with two underground basements and
- The available data of the subsoil morphology of the site's area.

5. Design Characteristics

The design characteristics of an earth retaining wall structure are the responses the values of which evaluate the reliability of an earth retaining wall structure. The two most important design variables of a "Berlin" type earth retaining wall structure are:

- Safety factor which is the response that represents the stability percentage of a structure and according to local and international legislation (European Committee for Standardization, Greek Ministry of Environment and Organization for Anti-seismic Planning And Protection & Greek Association of Civil Engineers) the minimum accepted value is 1,50 and
- Overall Cost which is a design variable that represents the material, the equipment, the excavation works and needed man-hours for the completion of a project. The lower the cost is the biggest chances a foundation engineering company has for the implementation of the construction.

6. Design Variables

In the beginning of the examined methodology for the simultaneous optimization of the two important design characteristics the needed design variables which affect directly those two responses were required. After the exception of design variables which are calculated directly from fundamental theories and calculations of civil and geotechnical engineering, the seven design variables the value of which is calculated from a range of values are:

- The steel section reinforcement
- The steel section size
- The steel section bonded length
- The axial distance between piles and/or anchors

- The anchoring level
- The anchoring angle and
- The anchors unbounded length

These seven design variables are presented to a cross section in Figure 1 and their upper and lower levels to Table 1.

7. Methodology Procedure

The design variables responsible for the response of safety factor and overall cost were examined based on the range their values can take. The first design variable which is the steel section type is discrete and it can take the values of the two options for vertical steel sections (double mirrored UPN or single HEB steel sections) that an engineer has when performs a “Berlin” type earth retaining wall structure. The other six of the control factors can take a value from a continuous range of values. Based on fundamental theories of engineering the upper and lower limit of the continuous range of the design variables values was provided. Desirability analysis for design variables with continuous range values need also a mid-value based on the upper and lower limits. Thus the analysis examines the behavior of continuous and discrete values.

The orthogonal array used for the seven design variables examined is an $L^{28} = 2^1 + 3^6$, where 28 experimental runs needed to be performed for the optimization with the use of one discrete with two values and six continuous design variables with three values.

The optimization approach for the two design characteristics is minimization, while safety factor needs to take a value close to 1,50. The increase of the safety factor has a proportional increase to the materials used and the time for the completion of the project and thus 1,50 is the desired (target) value.

8. Experiments

The orthogonal array chosen for the optimization of safety factor and overall cost provided the 28 experimental runs, which were used as inputs to the finite elements method which was conducted by Plaxis which is simulation software intended for geotechnical analysis of deformation and stability of soil structures. Cost was calculated by the nominal values of the materials, the equipment and the needed man-hours for the completion of the excavations and the earth retaining wall structure procedures. The area for cost calculations was chosen wisely for a wide range of implementation of the current systems used in the analysis of the present case study.

Safety factor and cost values for the desirability analysis calculations, as long as the combinations of the design variables for the 28 experiments are presented in Table 3 and Figure 2.

9. Findings

The data provided from the finite elements method were used for the calculations of the desirability analysis. Minitab is the statistical software where the fundamental theories of the desirability analysis assist the user of the current project for the simultaneous optimization of safety factor and overall cost for the “Berlin” type of the earth retaining wall structure. The results of the presented methodology are presented in the response optimizer data (Figure 3) and the optimization plots (Figure 4).

The best combination for the simultaneous optimization of safety factor and overall cost is for the following values of the design variables:

- Double UPN (2U) Steel section reinforcement
- 120 Steel section size
- 1,00m steel section underground length
- 2,00m steel section and anchor axial distance
- 0,50m anchoring level height
- 10° anchoring angle and
- 3,50m anchor’s bonded length

For the above design variables values the composite desirability of this project is 91% accurate because even if the predicted overall cost is predicted 100% accurate, safety factor value is 83% close to target. Safety factor value is 1,95 and overall cost for the presented case study is 2219,42€.

The above combination of the design variables was applied for the confirmation experiment of the study, where safety factor value was 2,06 and at overall cost of 2601,82€.

10. Critical Analysis

The output data from the desirability analysis and the confirmation experiment proved the following which are also presented in Table 4:

- The predicted values of cost from the desirability analysis and confirmation experiment are the lowest of the 28 measured experimental values.
- The predicted values of safety factor from the desirability analysis and confirmation experiment are larger than 1,50 which is the lower limitation based on local and international legislation.
- Based on the foundation engineering company’s results, even if the safety factor value was 24% lower than the predicted response of the confirmation experiment, the overall cost value is 50% larger. Thus the integrated desirability analysis implementation provided a more stable structure with half of the calculated cost.

11. Future Development

The methodology described here could be further developed. For instance the addition of other parameters could be taken into consideration such as the option of using shaft piles instead of the steel sections or for foundations with more than one row of pre-stressed anchors. Furthermore, the methodology could be also implemented in other types of earth retaining wall structures such as embedded or gravity walls.

12. Conclusion

The integrated desirability analysis implementation to the “Berlin” type earth retaining wall structure provided a combination of design variables for the more stable and financial beneficial solution that a civil or a geotechnical engineer search while he examines each case. This tool with a statistically proven low experimental runs execution can provide the values of the design variables responsible for the simultaneous optimization of safety factor and overall cost.

The combination of fundamental theories of engineering, statistical proven tools and finite elements analysis is an innovative methodology for the accurate prediction of the desired values of the responses needed to an earth retaining wall structure.

The precision of the results is shown to be unique but this has a direct relation to the data used as inputs of each case study. These are the geotechnical investigation data and the selection of the lower and higher value of the design variables.

The sharp accuracy of the integrated desirability analysis values are proven based on the confirmation experiment values and the composite desirability analysis percentage.

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Factor	Description	Unit	Low	Mid	High
A	Steel Sections Type	-	2U	N/A	HEB
B	Steel Sections Size	-	120	160	180
C	Soldier Pile’s Bonded Length	m	1,00	2.00	3.00
D	Axial Distance	m	1,00	1,50	2,00
E	Anchoring Level	m	0,50	1,00	1,50
F	Anchoring Angle`	deg	10,00	17,50	25,00
G	Anchor’s Unbonded Length	m	3,50	4,75	6,00

Table 1. Design variables, units and levels

	Safety Factor	Cost
Units		(€)
Approach	minimization to target	Minimization
Lower Value	1,50	3000
Target Value	1,50	-
Upper Value	2,50	10000
Weight	0,3	5
Importance	1	1

Table 2. Desirability analysis parameters

Order	Design Variables							Design Characteristics	
	Steel Section Type	Steel Section Size	Steel Section Length	Distance	Anchoring Level	Anchoring Angle	Anchoring Un-bonded leength	Safety Factor	Overall Cost
1	2	160	2,00	1,50	1,00	17,50	4,75	2,2993	3254,33
2	1	120	3,00	1,00	1,50	25,00	4,75	2,6062	7170,46
3	2	160	2,00	1,50	1,00	17,50	4,75	2,2993	6028,65
4	1	160	2,00	1,50	1,00	17,50	4,75	2,2941	4828,65
5	1	160	2,00	1,50	1,00	17,50	4,75	2,2941	4828,65
6	2	160	2,00	1,50	1,00	17,50	4,75	2,2993	6028,65
7	2	160	2,00	1,50	1,00	17,50	6,00	2,2993	6028,65
8	1	120	1,00	1,00	0,50	10,00	4,75	2,0750	5203,64
9	2	120	3,00	2,00	0,50	10,00	3,50	2,1548	4557,47
10	2	200	1,00	2,00	0,50	10,00	4,75	2,1046	4521,82
11	2	200	3,00	1,00	1,50	10,00	4,75	2,3008	10649,07
12	1	120	3,00	2,00	1,50	10,00	6,00	2,3153	3284,54
13	2	200	1,00	1,00	0,50	25,00	6,00	2,3635	9129,90
14	1	160	2,00	1,50	1,00	17,50	4,75	2,2941	4828,65
15	1	160	2,00	1,50	1,00	17,50	6,00	2,2941	4828,65
16	1	160	2,00	1,50	1,00	17,50	4,75	2,2941	4828,65
17	2	120	1,00	2,00	1,50	25,00	3,50	2,1571	3654,13
18	2	120	1,00	1,00	1,50	10,00	4,75	2,2704	7271,75
19	2	200	3,00	2,00	1,50	25,00	4,75	2,6174	5865,23
20	2	160	2,00	1,50	1,00	17,50	4,75	2,2993	6028,65
21	2	120	3,00	1,00	0,50	25,00	4,75	2,1836	8205,58
22	1	120	1,00	2,00	0,50	25,00	4,75	2,1331	2884,95
23	1	160	2,00	1,50	1,00	17,50	6,00	2,2941	4828,65
24	1	200	1,00	1,00	1,50	25,00	4,75	2,3256	7308,25
25	2	160	2,00	1,50	1,00	17,50	4,75	2,2993	6028,65
26	1	200	3,00	2,00	0,50	25,00	3,50	2,3331	4462,79
27	1	200	3,00	1,00	0,50	10,00	6,00	2,2792	9354,95
28	1	200	1,00	2,00	1,50	10,00	4,75	2,2835	3875,88

Table 3. Desirability analysis experimental runs and finite elements analysis results.

	Foundation engineering Co. results	Desirability Analysis	Confirmation Experiment	Error (%)	Range
Safety factor <minimize to target>	1,65	1,95	2,05	5%	1.50 to 2.50
Cost (€) <minimize>	5290,26	2219,42	2601,82	15%	3000 to 10000

Table 4. Desirability analysis, confirmation experiment, error and range results

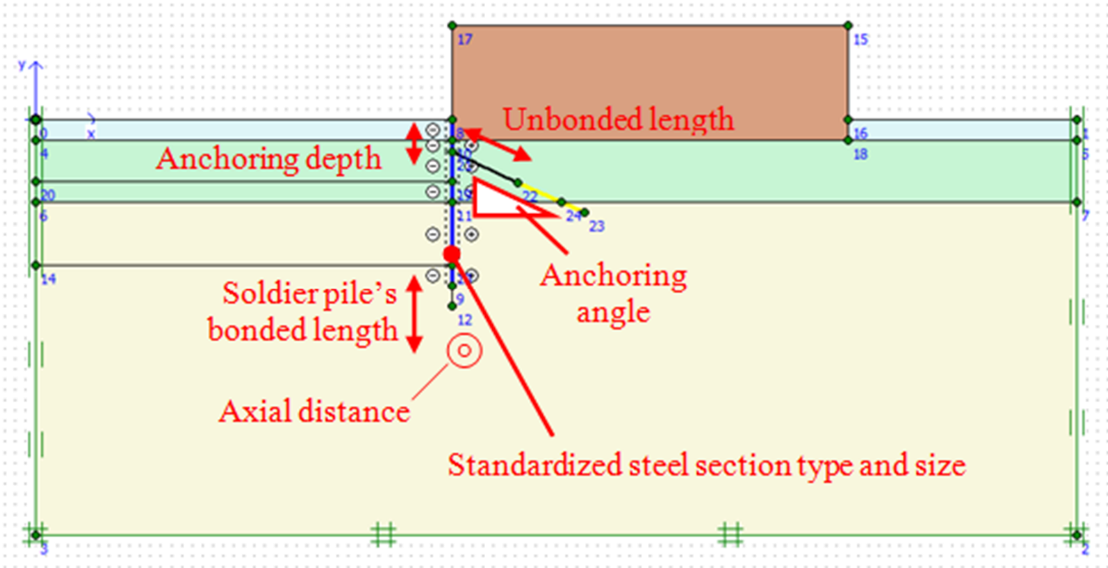

Figure 1: Design variables presentation

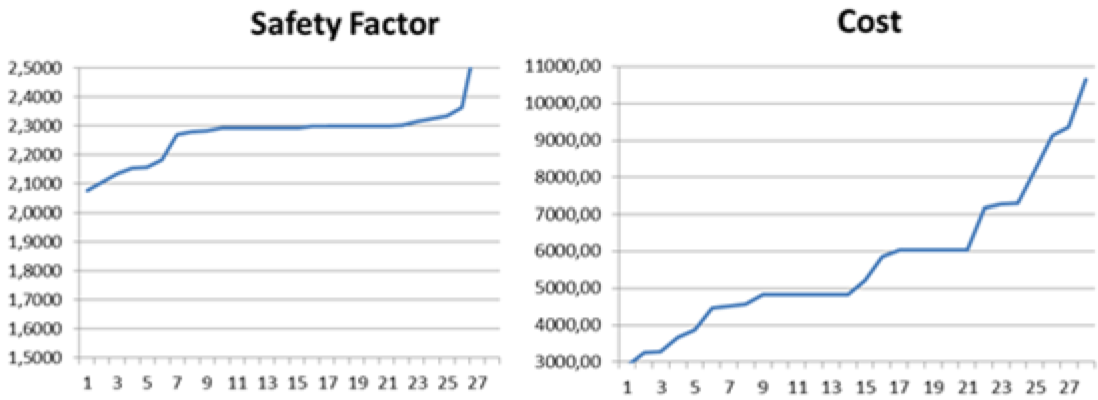

Figure 2: Safety Factor and cost response based on 28 experiments (sorted)

Response Optimization

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Parameters

               Goal      Lower   Target    Upper  Weight  Import
Safety Factor Target      1,5     1,50     2,50     0,3       1
Cost          Minimum  3000,0  3000,00  10000,0     5,0       1


Global Solution

B:Type       =    -1  (2U)
B:Size       =   120
B:Length     =     1
B:Distance   =     2
A:Level      =   0,5
A:Angle      =    10
A:Lgh (le)   =   3,5


Predicted Responses

Safety Factor  =      1,95  ,   desirability =   0,834851
Cost           =   2219,42  ,   desirability =   1,000000

Composite Desirability = 0,913702
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Figure 3: Desirability analysis results

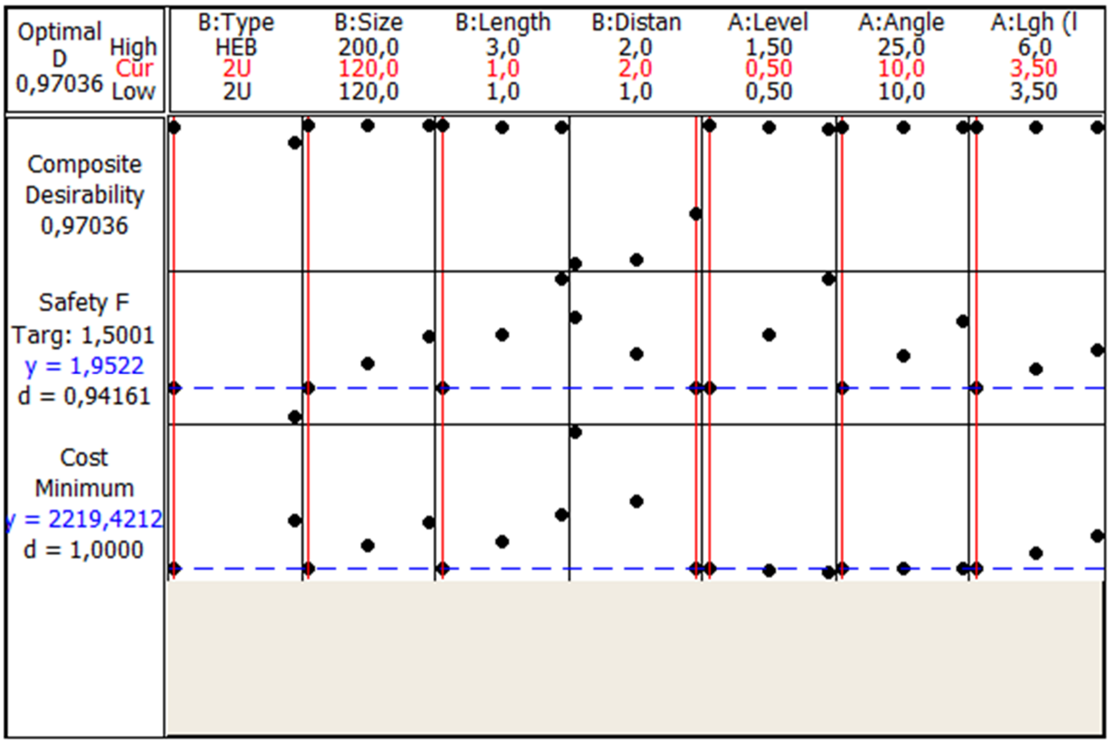

Figure 4: Optimization plots