Taguchi implementation for safety-factor optimisation in engineering structures

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ABSTRACT: This article presents the development of a novel methodology for the implementation of quality tools in the engineering field of earth retaining wall structures for process optimisation. Finite elements analysis (FEA) of the structure is conducted by obtaining the numerical model parameters through Taguchi analysis to optimise the safety factor. The response of the safety factor, the most important design characteristic examined in the presented implementation, depends on design variables named control factors. These factors are relative to soldier piles and temporary pre-stressed ground anchors' properties, which are used in the performed excavation stages for the completion of a project. Through successful implementation of quality tools as Taguchi in FEA analysis, the best combination of design variables can be obtained to optimise the structure's safety factor conducting the minimum possible experimental runs, whereas each experiment is substituted by a FEA calculation.

INTRODUCTION

In order to increase their competitiveness, companies need to evolve their products and processes. One successful way this evolution can take place is under the adoption of methodologies based on quality theories. Engineering fields, such as earth retaining wall structures could implement methods like Taguchi analysis for the optimisation of important design characteristics.

One of the most important design characteristics regarding the Taguchi analysis implementation is the safety factor. This response is the ratio of the breaking stress of a structure to the estimated maximum stress in ordinary use. Local and international legislation provides the lower acceptable limit of a structure which is 1.50 [1-7]. The higher the safety factor safety is, the more robust and secure a construction is.

METHODOLOGY DEVELOPMENT

The methods for the optimisation of a design characteristic in engineering structures can be divided into two categories:

- The first category is based on the range analysis that takes place. This range could concern the entity of a structure (for instance safety factor) or could concern a certain characteristic, such as the most proper material used.
- The second category is based on the methodology optimisation that is achieved. Methodologies which could be named are genetic algorithms, non-linear time history analysis, graph theoretical operators, chaos-theory algorithm.

The subject analysed in this article is the latest evolution of the optimisation of safety factor for earth retaining wall structures.

The first approach was shown in the *First European Research Conference on Continuous Improvement and Lean Six Sigma* in Scotland (2008), where Telis et al presented a paper entitled: *Quality improvement of safety factor in construction design* [8]. This paper analysed Taguchi methodology and ANOVA treatment adopted in the Improve Phase of the define measure analyse improve, control (DMAIC) cycle dictated by Six Sigma principles. This was supplemented by a two level, seven design variables with seven interactions analysis for the maximisation of safety factor.

In 2008, Telis et al also presented at the *eRA 3 - Conference for the Contribution of Information Technology to Science, Economy, Society and Education*, a paper entitled: *Parametric optimisation of safety factor in construction engineering* [9]. This paper outlined the simplest approach an engineer could follow for the optimisation of safety factor. With the minimum number of eight experimental runs for seven design variables of two levels each, a further approach for the selection of the design variables responsible for the value of safety factor was implemented.

Finally, a paper by Telis et al was published in 2011 in the *International Journal of Experimental Design and Process Optimisation*, entitled: *Optimisation of safety factor in the designing phase of a bracing study* [10]. In this study, Taguchi analysis and ANOVA treatment were examined one step further for the optimisation of the safety factor in an earth retaining wall structure.

The article presented here shows the evolution of an engineering model to implement Taguchi analysis via the addition of another level of control to the design variables and an alteration to the design variables for most accurate and better calculations for the optimisation of safety factor. The examined case study has also been changed for easier adoption to the majority of earth retaining wall structures.

CASE STUDY

The case study presented in this article is a real life project located in the centre of Athens, Greece, which was assigned to a local foundation engineering company.

The examined case study is an earth retaining structure of 7.00 m depth next to an adjacent two storey building without basement (worst case scenario), for the construction of a six storey building with two underground basements.

The procedure being performed is based on the *Berlinoise* earth retaining wall structure type. This is constructed with vertical soldier piles at regular intervals, aligned with a pile cap, a temporary pre-stressed anchors row installed in certain positions and a layer of shotcrete placed in the space between the piles [11].

DESIGN VARIABLES

The seven design variables responsible for the response of safety factor, named control factors are:

- Beams type: this control factor provides the way the soldier piles' standardised steel sections are used in order to retain the earth masses of the adjacent properties. The two methodologies examined here are with HEB beams and double UNP beams placed mirrored named 2U in the following steps.
- Beams size: this is a number that shows the soldier piles' standardises steel section size.
- Beams length: this design variable provides the bonded (restrained) depth, which is under the final excavation level.
- Distance: this control factor describes the regular intervals distance between beams and/or anchors.
- Anchoring level: this level shows the depth of the installation of the row of temporary pre-stressed anchors.
- Anchoring angle: this factor presents the inclination of the row of the temporary pre-stressed anchors to the level of the horizon.
- Anchoring unbonded length: this variable presents the unbounded length of the row of the temporary pre-stressed anchors.

Table 1: Factors and levels.

Factor	A	B	C	D	E	F	G
Description	Beams type	Beams size	Beams length	Distance	Anchoring level	Anchoring angle	Anchoring unbounded length
Units			(m)	(m)	(m)	(deg)	(m)
Level 1	2 U	120	1.00	1.00	0.50	10.00	3.50
Level 2	HEB	160	2.00	1.50	1.00	17.50	4.75
Level 3		200	3.00	2.00	1.50	25.00	6.00

EXPERIMENTAL PROCEDURE

The approach for the optimisation of safety factor in this *Berlinoise* earth retaining wall structure case study is based on the Taguchi analysis.

Table 2: Experimental procedure and measurements.

Exp	A	B	D	C	E	F	G	Safety Factor
	Type	Size	Length	Distance	Level	Angle	Unbounded	
1	1	120	1,00	1,00	0,50	10,00	3,50	2,0831
2	1	120	1,00	1,00	0,50	10,00	4,75	2,1012
3	1	120	1,00	1,00	0,50	10,00	6,00	2,1614
4	1	160	2,00	1,50	1,00	17,50	3,50	2,2097
5	1	160	2,00	1,50	1,00	17,50	4,75	2,3001
6	1	160	2,00	1,50	1,00	17,50	6,00	2,4113
7	1	200	3,00	2,00	1,50	25,00	3,50	2,3853
8	1	200	3,00	2,00	1,50	25,00	4,75	2,4683
9	1	200	3,00	2,00	1,50	25,00	6,00	2,5419
10	1	120	1,00	1,50	1,00	25,00	3,50	1,8817
11	1	120	1,00	1,50	1,00	25,00	4,75	2,1777
12	1	120	1,00	1,50	1,00	25,00	6,00	2,2240
13	1	160	2,00	2,00	1,50	10,00	3,50	2,1721
14	1	160	2,00	2,00	1,50	10,00	4,75	2,2261
15	1	160	2,00	2,00	1,50	10,00	6,00	2,2739
16	1	200	3,00	1,00	0,50	17,50	3,50	2,2894
17	1	200	3,00	1,00	0,50	17,50	4,75	2,3170
18	1	200	3,00	1,00	0,50	17,50	6,00	2,4108
19	1	120	2,00	1,00	1,50	17,50	3,50	2,1860
20	1	120	2,00	1,00	1,50	17,50	4,75	2,2313
21	1	120	2,00	1,00	1,50	17,50	6,00	2,3016
22	1	160	3,00	1,50	0,50	25,00	3,50	2,1003
23	1	160	3,00	1,50	0,50	25,00	4,75	2,1131
24	1	160	3,00	1,50	0,50	25,00	6,00	2,1941
25	1	200	1,00	2,00	1,00	10,00	3,50	2,0756
26	1	200	1,00	2,00	1,00	10,00	4,75	2,0924
27	1	200	1,00	2,00	1,00	10,00	6,00	2,1436
28	2	120	3,00	2,00	1,00	17,50	3,50	2,2952
29	2	120	3,00	2,00	1,00	17,50	4,75	2,3628
30	2	120	3,00	2,00	1,00	17,50	6,00	2,4349
31	2	160	1,00	1,00	1,50	25,00	3,50	2,1862
32	2	160	1,00	1,00	1,50	25,00	4,75	2,3093
33	2	160	1,00	1,00	1,50	25,00	6,00	2,4843
34	2	200	2,00	1,50	0,50	10,00	3,50	2,1985
35	2	200	2,00	1,50	0,50	10,00	4,75	2,2058
36	2	200	2,00	1,50	0,50	10,00	6,00	2,2136
37	2	120	2,00	2,00	0,50	25,00	3,50	2,2304
38	2	120	2,00	2,00	0,50	25,00	4,75	2,3233
39	2	120	2,00	2,00	0,50	25,00	6,00	2,4318
40	2	160	3,00	1,00	1,00	10,00	3,50	2,2744
41	2	160	3,00	1,00	1,00	10,00	4,75	2,2828
42	2	160	3,00	1,00	1,00	10,00	6,00	2,3556
43	2	200	1,00	1,50	1,50	17,50	3,50	2,1851
44	2	200	1,00	1,50	1,50	17,50	4,75	2,2528
45	2	200	1,00	1,50	1,50	17,50	6,00	2,3098
46	2	120	3,00	1,50	1,50	10,00	3,50	2,1782
47	2	120	3,00	1,50	1,50	10,00	4,75	2,2126
48	2	120	3,00	1,50	1,50	10,00	6,00	2,2646
49	2	160	1,00	2,00	0,50	17,50	3,50	1,8557
50	2	160	1,00	2,00	0,50	17,50	4,75	2,0022
51	2	160	1,00	2,00	0,50	17,50	6,00	2,1081
52	2	200	2,00	1,00	1,00	25,00	3,50	2,2695
53	2	200	2,00	1,00	1,00	25,00	4,75	2,3556
54	2	200	2,00	1,00	1,00	25,00	6,00	2,4478

This technique uses orthogonal arrays which provide a minimum number of experimental runs for a number of control factors and their levels and interactions. This is based on theories and principles of statistics. The orthogonal array used in this experimental procedure is:

$$L_{54} = 2^1+3^6 \tag{1}$$

which describes 54 experimental runs with the use of a factor with two levels and six factors with three levels each. The design variables and their levels are shown in Table 1. Moreover, the following three most important interactions of the control factors have been examined CxG, ExG and FxG [12].

The formation of this orthogonal array is presented in Table 2.

The experiments were used as inputs in the finite elements analysis (FEA) software (Plaxis), which provided the safety factor value for each run. The accuracy up to the fourth digit that FEA software provided to the user offered an applicable means and not signal-to-noise framework. The results of these measurements are shown in the final column of Table 2.

TAGUCHI FINDINGS

For the Taguchi implementation, in order to discover the optimum combination of the design variables, the following were used:

- Safety factor measurements for the 54 experimental runs;
- The orthogonal array arrangement;
- The approach of safety factor which is maximisation;
- The levels of the designing variables;
- The interactions of the design variables.

The above were used as input to the statistical software MiniTab, which provided the response table means (Figure 1), the main effect plot for means (Figure 2) and the interaction plot for means (Figure 3) of the Taguchi analysis [12].

Response Table for Means

Level	B:Type	B:Size	B:Length	B:Distance	A:Level	A:Angle	A:Lgh (le)
1	2,225	2,227	2,146	2,280	2,186	2,195	2,170
2	2,260	2,214	2,277	2,202	2,255	2,248	2,241
3		2,287	2,305	2,246	2,287	2,285	2,317
Delta	0,035	0,072	0,158	0,079	0,102	0,089	0,148
Rank	7	6	1	5	3	4	2

Figure 1: Response table for means (MiniTab results).

From these three figures, the calculation of safety factor based on the average value for the 54 experimental runs (T_{SF}) and the levels of the factors responsible for the optimisation of the design characteristic, is calculated via Equation (2).

$$\begin{aligned} U_{SF} &= \overline{T_{SF}} + (C3 - \overline{T_{SF}}) + (G3 - \overline{T_{SF}}) + (E3 - \overline{T_{SF}}) + (F3 - \overline{T_{SF}}) + (D1 - \overline{T_{SF}}) + (B3 - \overline{T_{SF}}) \Rightarrow \\ U_{SF} &= 2.5477 \end{aligned} \tag{2}$$

CONFIRMATION EXPERIMENT

Based on the Taguchi approach results, the optimum combination for the maximisation of safety factor is for HEB 200 standardised steel section beams bonded 3.00 m under the final excavation level. Temporary pre-stressed anchors are placed 1.50 m under the higher level of the beam (±0.00) at 25^{o} inclination and 6.00 m unbounded length. The distance between piles and/or anchors is 1.00 m. The above values were implemented to the FEA software, where the safety factor value was calculated 2.6188. This value compared to the Taguchi analysis result has an error of 2.8%.

CRITICAL ANALYSIS

The Taguchi technique was used for the maximisation of safety factor in a *Berlinoise* earth retaining wall structure. This methodology provided the optimum combination of design variables levels for this optimisation. The error between the values of the calculated safety factor and the confirmation experiment shows the accuracy of this methodology. Moreover, the confirmation's experiment value is larger than the calculated, which could be explained with the approach followed for the optimisation which is maximisation.

Furthermore, the range of the measured values of safety factor is between 1.85 and 2.54, while the optimum value of safety factor is 2.62 which is the larger of the 54 measured. Thus, this methodology finds the behaviour and how each factor affects the safety factor value and calculates its optimum value.

The outcomes of the methodology presented in this article are the evolution of the preliminary findings presented previously, where the control factors focus directly on the variables, which control the safety factor behaviour and concern a wider range of *Berlinoise* earth retaining wall structures.

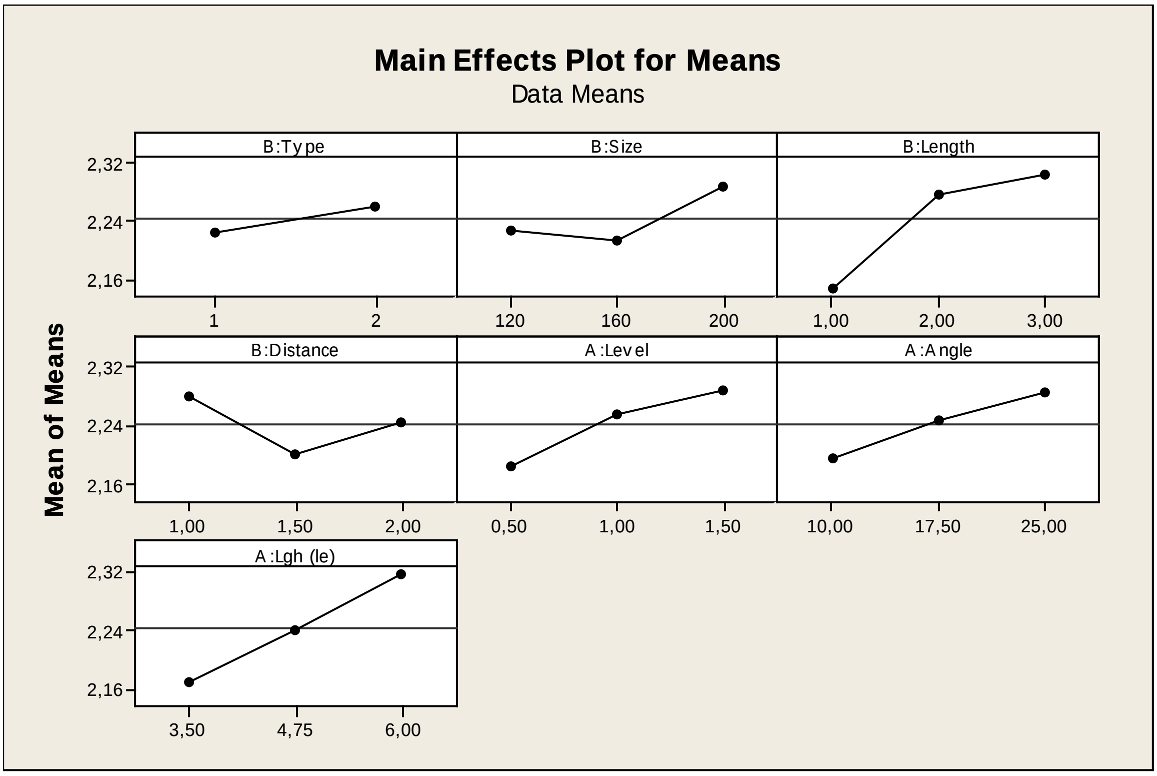

Figure 2: Main effect plot for means (MiniTab results).

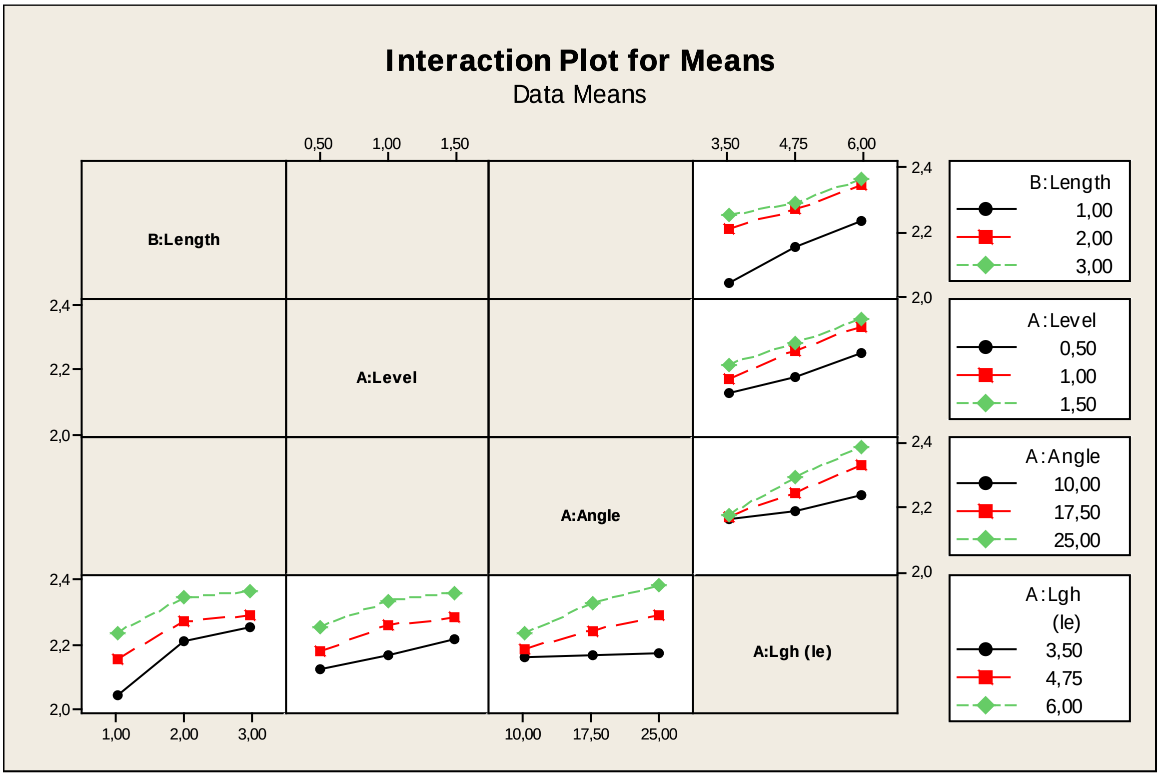

Figure 3: Interaction plot for means (MiniTab results).

CONCLUSIONS

To sum up, the Taguchi approach can be implemented in the majority of engineering projects for the optimisation of the most important response. The approach followed is directly compared to process or product optimisation in case studies in the field of quality.

The procedure for the optimisation of a design characteristic is by finding the design variables responsible for its performance and by adopting a methodology, which suits the data and the approach for each case study.

In *Berlinoise* earth retaining wall structure, the methodology implemented for the maximisation of the safety factor provided accurately the optimum combination of the design variables. The precision of the results depends on the selection of the design variables and their levels, and by the geotechnical data analysis of the subsoil on which the retaining wall structure was based.

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