Determining Of Safety Factors For Cantilever Retaining Wall With Mathematical Model

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Abstract

In the conventional design of cantilever retaining wall, trial-and-error method has been used to determine wall dimensions which satisfies the stability conditions of wall. This method takes time in design period and is not possible to know which parameter is the most effective in the design. In this study, safety factors of the cantilever retaining wall which play a crucial role in stability of the wall have been investigated to determine with mathematical model. In computing of safety factors of sliding, overturning and slope stability mathematically, Taguchi method which is a statistical method has been employed. For different situations Signal/Noise (S/N), variance and optimization analyses have been performed separately by using L_{16} orthogonal design tables. At result of these analysis, effect of the length of base, the toe extension, the thickness of base, the angle of front face of wall and the angle of internal friction on safety factors of sliding, overturning and slope stability have been studied. Consequently, obtained relative errors from mathematical model safety factors demonstrate that these models are efficient and reliable in the design of cantilever retaining wall.

Keywords: Cantilever retaining wall, Taguchi method, mathematical model, statistical analysis.

1 Introduction

In today's geotechnical engineering, the time has become important criteria in terms of completing the design of geotechnical structures as soon as possible. In the traditional design of cantilever retaining wall which is a geotechnical structure, stability analyses like slide check, overturning check, slope stability and so on, have been conducted according to selected wall dimensions [1, 2]. This process continues by selecting new wall dimensions each time until stability analyses are satisfied. Such time-consuming design methods have brought new methods to make design in a shorter time. Taguchi method which one of the methods to provide making design in shorter time give information about effective parameter on design and the optimum design in case of maximum or minimum safety factor. Taguchi method based on statistical analysis has been put forward by Genichi Taguchi with the aim of increasing quality of experiment in 1950s [3]. This method not only make it possible obtain experiments with less study but also find the best values between all parameters and all levels of parameters.

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The Taguchi method, which is used especially in the experimental design and the quality management, is widely used in the designs of engineering to investigate the design criteria. In this method, it is possible to gain the effects of parameters on design by performing less experiments without making many experiments with orthogonal array [4]. Studies of determination of safety factor of slope stability with mathematical model and investigation of design criteria of gabion retaining wall which is another type of retaining wall have been carried out by using Taguchi Method [5, 6].
In this study, mathematical models have been submitted to determine safety factors of sliding, overturning and slope stability by using Signal/Noise (S/N) ratios identified by Taguchi. The effect of design parameters like the length of base, the toe extension, the thickness of base, the angle of front face of wall and the angle of internal friction on the design has investigated by Taguchi Method. Mathematical models proposed for calculation of safety factors of sliding, overturning and slope stability according to selected design parameters. To investigate all combination of all parameters 16 cantilever retaining wall design have been analyzed by using L_{16} orthogonal design table and has been performed fractional factorial design for four levels of five parameters.

2 Taguchi Method

Taguchi Method is a robust and easily applicable method, because it reaches results in less time and to determine effects of the parameters on the result trustworthily. It reduces the cost of investigation and performs parametric analysis. Normally, to investigate effect of five parameters with four levels on safety factors of sliding, overturning and slope stability $4^5 = 1024$ design must be carried out. In this method, it is possible to obtain parameters effect on the result with 16 designs by means of orthogonal array. In this study, L_{16} (4^5) orthogonal array (five parameters and four level) has been employed and it is given Table 1.

Table 1: L_{16} (4^5) orthogonal array

Design No	Parameters and Levels				
	P_1	P_2	P_3	P_4	P_5
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	2	3	4
6	2	2	1	4	3
7	2	3	4	1	2
8	2	4	3	2	1
9	3	1	3	4	2
10	3	2	4	3	1
11	3	3	1	2	4
12	3	4	2	1	3
13	4	1	4	2	3
14	4	2	3	1	4
15	4	3	2	4	1
16	4	4	1	3	2

In the Taguchi analyses of cantilever retaining wall design, selected parameters and their levels are given in Table 2. In determination of lower and upper limits of selected parameters national and design codes have been taken into consideration [7-9]. While the X_1 and the X_3 are varying depending on the wall height (H), the X_2 varies depending on the X_1.

Table 2: Selected parameters and their levels

Parameter	Level 1	Level 2	Level 3	Level4
Length of base, X_1	0.25H	0.50 H	0.75 H	1.00 H
Toe extension, X_2	0.15 X_1	0.30 X_1	0.45 X_1	0.60 X_1
Thickness of base, X_3	0.06 H	0.09 H	0.12 H	0.15 H
Angle of front face, X_4 (%)	0	1	2	4
Angle of internal friction, Ø (°)	20	27	34	41

In Taguchi Method, effects of the parameters on the results and mathematical model have been determined with the S/N ratios. Signal/Noise ratio (S/N) is described by Taguchi with aim of decreasing variance and is used as performance criteria in experiment design. S/N ratio divided into three depended on purpose of application; smaller is better, nominal is best, larger is better, are given in respectively Equation 1, Equation 2 and Equation 3. In this study, S/N analyses has been performed according to the target state of "Larger is better" which maximize the response. According to Taguchi, the variance which is defined as difference from the target value has been decreased and the signal has been increased in case of S/N ratio is maximum [4]. Variance is a degree of distribution of a number sequence around arithmetic mean of this number sequence.

$$\mathrm{S/N} = -10\mathrm{xlog}\left(\sum (\mathrm{Y}^2)/\mathrm{n}\right) \tag{1}$$

$$\mathrm{S/N} = -10\mathrm{xlog}(\bar{\mathrm{Y}}/\sigma^2) \tag{2}$$

$$\mathrm{S/N} = -10\mathrm{xlog}\left(\sum (1/\mathrm{Y}^2)/\mathrm{n}\right) \tag{3}$$

Here Y is the response value, n is the number of repetitions, $\overline{Y}$ is arithmetic mean and σ is standard deviation.

3 Numerical and Statistical Analyses

In numerical analyses, the cantilever retaining wall height (H=6m), top stem thickness of wall (b=0.25m) unit volume weight of soil ($\gamma_s = 18kN/m^3$), unit weight of concrete, ($\gamma_c = 25kN/m^3$) and friction angle between base and soil ($\delta = 2/3Ø$) are taken same for 16 designs. Acting loads on cantilever retaining wall and selected wall dimensions which are used for determination of safety factors of sliding, overturning and slope stability of wall are given in Figure 1.

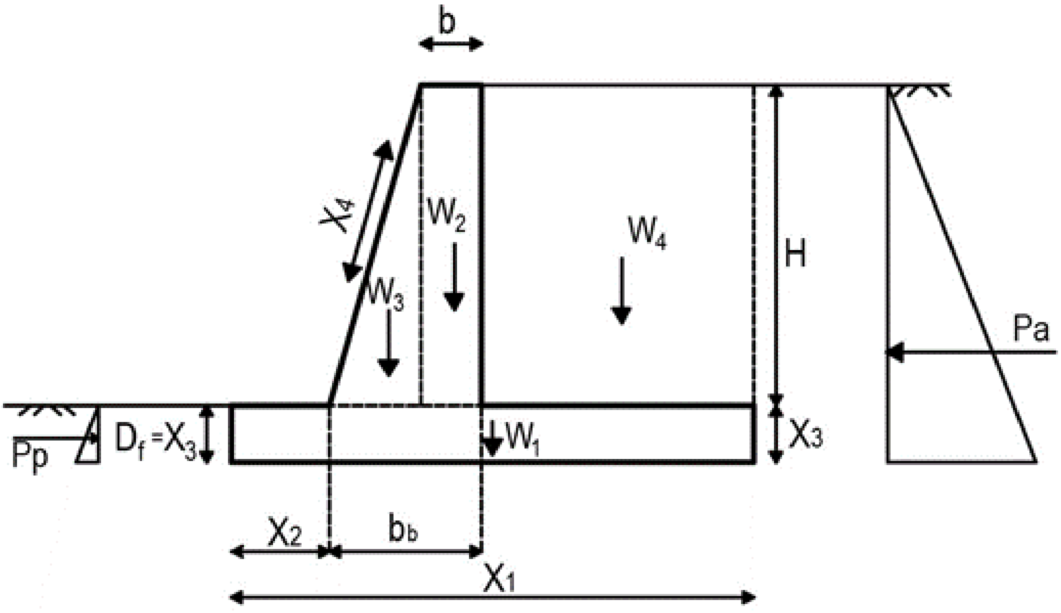

Figure 1: Cantilever Retaining Wall Dimensions and Acting Loads

In the cantilever retaining wall design, the same soil properties have been taken into account for foundation soil and backfill of wall with a single value of unit volume weight of soil (18 kN/m^3) and four different value of angle of internal friction (20-27-34-41°). Value of the internal friction angle which uses in design changes according to L_{16} orthogonal array design table. In the checks of sliding, overturning and slope stability, analysis of cantilever retaining wall have been conducted according to single-layer cohesionless soil condition without ground water. Due to the fact that the overturning of the wall is less likely than slide, passive soil pressure has not taken into consideration for obtaining of safety factor of overturning. In Table 3, mathematical formulas which use for obtaining of safety factors of sliding and overturning according to GEO 5 computer program [10] have given detailed. Safety factor of slope stability has obtained by Bishop method from computer program.

Table 3: Used mathematical formulas for determining safety factors of sliding and overturning

Bottom thickness of the stem	$\mathrm{b_b}=(\mathrm{H}-\mathrm{X_3})*\mathrm{X_4}+\mathrm{b}$
Weight of wall	$\mathrm{W_1}=\mathrm{X_1}\ \mathrm{X_3}\ \gamma_c$ $\quad \mathrm{W_2}=\mathrm{b\ H}\ \gamma_c$ $\mathrm{W_3}=0.5\,(\mathrm{b_b}-\mathrm{b})\ \mathrm{H}\ \gamma_c$
Weight of backfill	$\mathrm{W_4}=(\mathrm{X_1}-\mathrm{X_2}-\mathrm{b_b})\ \mathrm{H}\ \gamma_s$
Active soil pressure	$\mathrm{P_a}=0.5\ \mathrm{H}^2\ \gamma_s\ \mathrm{K_a}$
Passive soil pressure	$\mathrm{P_p}=0.5\ \mathrm{D_f}^2\ \gamma_s\ \mathrm{K_p}$
Active soil pressure coefficient	$\mathrm{K_a}=\tan^2(45-\text{Ø}/2)$
Passive soil pressure coefficient	$\mathrm{K_p}=\tan^2(45+\text{Ø}/2)$
Safety factor of sliding	$\mathrm{F_s\,(sliding)}=\frac{(\mathrm{W_1+W_2+W_3+W_4})\tan\delta}{\mathrm{P_a-P_p}}$
Safety factor of overturning $\mathrm{F_s\,(overturning)}=\frac{0.5\mathrm{W_1X_1}+\mathrm{W_2}(\mathrm{b_b}-0.5\,\mathrm{b}+\mathrm{X_2})+\mathrm{W_3}(0.667\,(\mathrm{b_b}-\mathrm{b})+\mathrm{X_2})+0.5\,\mathrm{W_4}(\mathrm{X_1}+\mathrm{X_2}+\mathrm{b_b})}{0.333\,\mathrm{P_a}\,(\mathrm{H}+\mathrm{X_3})}$	

By using orthogonal array given in Table 1 and parameter levels given in Table 2, revised L_{16} design table has demonstrated in Table 4. Cantilever retaining wall designs has been conducted in computer program according to revised design table and end of the analysis safety factors of sliding, overturning and slope stability have been obtained (Table 4).

Table 4: Cantilever retaining wall Taguchi design table and results of numerical analyses

Design No	Parameter Levels					Safety Factor (Fs)		
	X_1	X_2	X_3	X_4 (%)	Ø (°)	Sliding	Overturning	Slope Stability
1	0.25H	$0.15X_1$	0.06H	0	20	0.22	0.35	0.75
2	0.25H	$0.30X_1$	0.09H	1	27	0.34	0.42	1.09
3	0.25H	$0.45X_1$	0.12H	2	34	0.52	0.48	1.48
4	0.25H	$0.60X_1$	0.15H	4	41	0.97	0.53	1.96
5	0.50H	$0.15X_1$	0.09H	2	41	2.48	3.11	2.18
6	0.50H	$0.30X_1$	0.06H	4	34	1.08	2.24	1.54
7	0.50H	$0.45X_1$	0.15H	0	27	0.59	1.36	1.27
8	0.50H	$0.60X_1$	0.12H	1	20	0.24	0.92	0.84
9	0.75H	$0.15X_1$	0.12H	4	27	1.15	3.68	1.51
10	0.75H	$0.30X_1$	0.15H	2	20	0.54	2.55	1.06
11	0.75H	$0.45X_1$	0.06H	1	41	2.34	6.13	2.10
12	0.75H	$0.60X_1$	0.09H	0	34	1.11	3.65	1.58
13	1.00H	$0.15X_1$	0.15H	1	34	3.04	8.31	2.26
14	1.00H	$0.30X_1$	0.12H	0	41	4.77	11.18	2.67
15	1.00H	$0.45X_1$	0.09H	4	20	0.57	4.38	1.00
16	1.00H	$0.60X_1$	0.06H	2	27	0.78	4.94	1.23

Statistica [11] computer program has been employed for statistical analyses. In Figure 2, calculated S/N ratios are given by using safety factors obtained from the numerical analyses. Graphical representation of average S/N ratios corresponding to each parameter level for safety factors of sliding, overturning and slope stability are given respectively in Figure 3, Figure 4 and Figure 5.

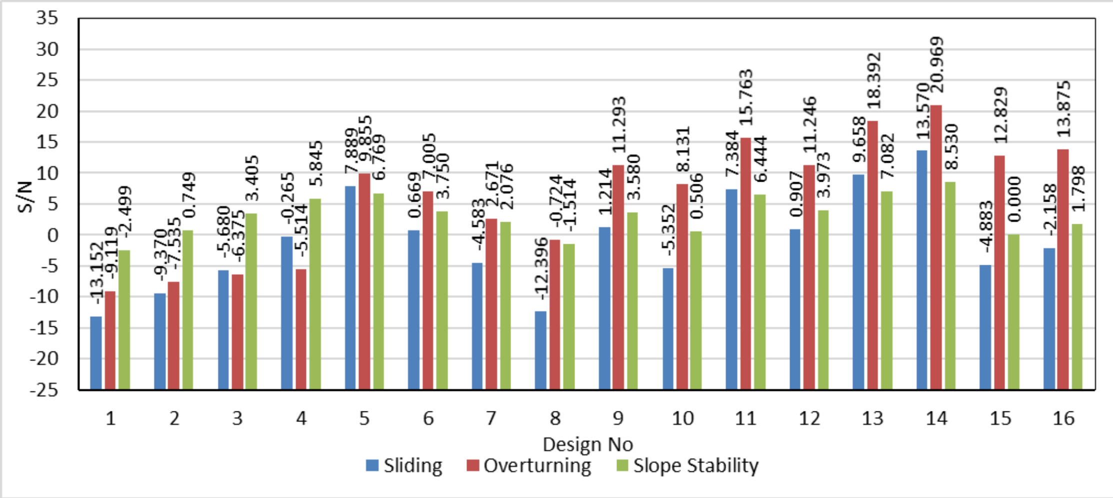

Figure 2: Cantilever Retaining wall S/N ratios

In Figure 2, it is clear that the most change of average S/N ratio of safety factor of sliding is belonging the angle of internal friction and the second most change is the length of base. While the length of base, the angle of internal friction and the thickness of base shows increasing, the toe extension and the angle of front face generally shows decreasing with increasing parameter level.

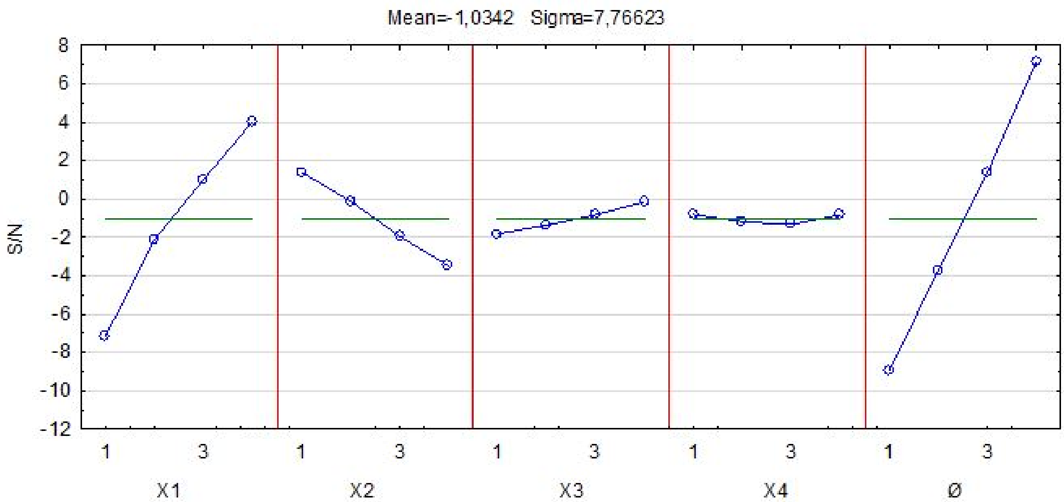

Figure 3: Change between average S/N ratio and safety factor of sliding

According to Figure 3, which is given for safety factor of overturning, the highest change of average S/N ratio is the length of base and the lowest one is the angle of front face. While levels of parameter increase, change of average S/N ratios of the length of base and the angle of internal friction go up and the others go down.

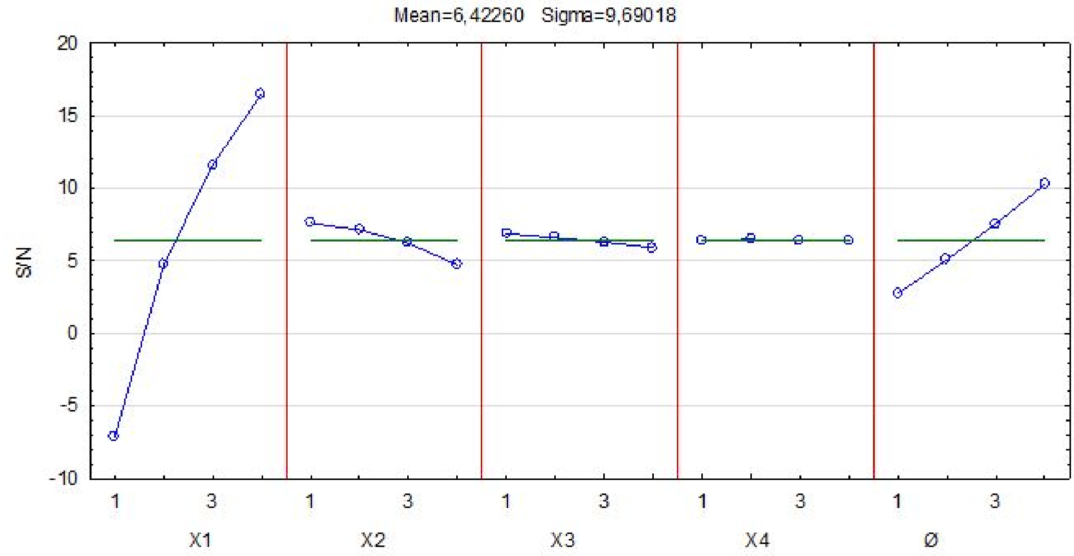

Figure 4: Change between average S/N ratio and safety factor of overturning

In Figure 3, behavior of parameters in changing of average S/N ratios is like change between average S/N ratios and safety factor of sliding.

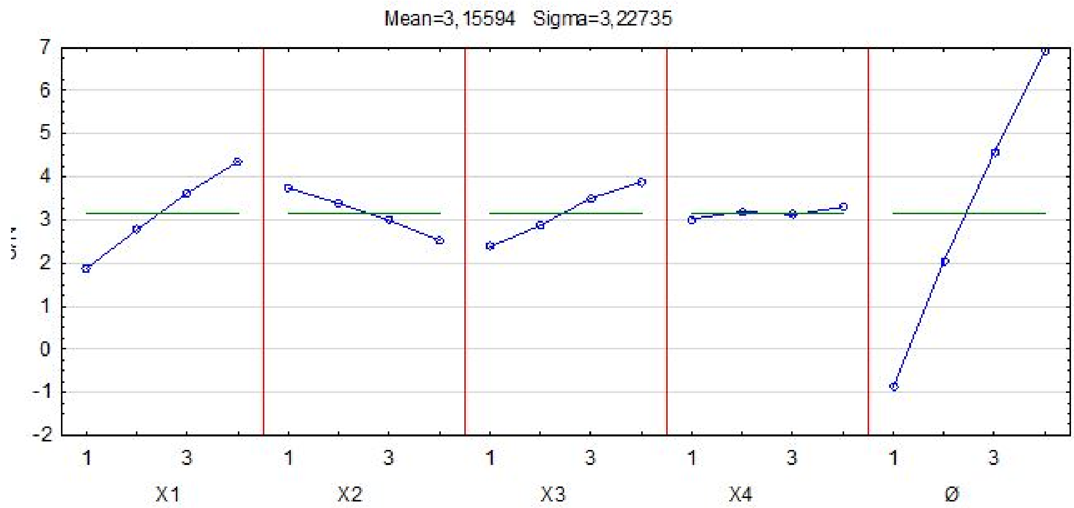

Figure 5: Change between average S/N ratio and safety factor of slope stability

In the investigation of effect of parameters on the design of cantilever retaining wall, parameters of the length of wall, the toe extension, the thickness of base, the angle of front face and the angle of internal friction are taken into consideration. To determine effect rate of parameters has been employed variance analysis. Variance is defined as sum of squares of deviations from arithmetic mean of data. Variance, a statistical term, shows distance between each number in the sequence and average of all the numbers in the series.
Effect rates of design parameters on the safety factors for H=6m is given in Table 5. It observes that parameter which is the most effective on safety factors of sliding and slope stability is the angle of internal friction which has the most value of variance. The most efficient parameter is the length of base for safety factor of overturning.

Table 5: Cantilever retaining wall results of variance analyses

Parameter		Degree of Freedom (DOF)	Sum of Squares (Ss)	Variance MS	Effect Rate (P) (%)
Sliding	Length of Base, X_1	3	273.017	91.006	30.177
	Toe Extension, X_2	3	54.253	18.084	5.997
	Thickness of base, X_3	3	6.279	2.093	0.694
	Angle of front face, X_4 (%)	3	0.809	0.270	0.089
	Angle of internal friction, Ø (°)	3	570.356	190.119	63.043
Overturning	Length of Base, X_1	3	1262.262	420.7541	89.62
	Toe Extension, X_2	3	19.420	6.4732	1.38
	Thickness of base, X_3	3	2.046	0.6820	0.15
	Angle of front face, X_4 (%)	3	0.024	0.0080	0.00
	Angle of internal friction, Ø (°)	3	124.741	41.5803	8.86
Slope Stability	Length of Base, X_1	3	13.769	4.590	8.813
	Toe Extension, X_2	3	3.251	1.084	2.081
	Thickness of base, X_3	3	5.325	1.775	3.408
	Angle of front face, X_4 (%)	3	0.160	0.053	0.102
	Angle of internal friction, Ø (°)	3	133.731	44.577	85.595

Results of optimization analyses obtained from statistical analyses for safety factors of sliding, overturning and slope stability are given respectively in Table 6, Table 7 and Table 8.

Table 6: Optimization results for maximum safety factor of sliding

Parameter	Level	Level Description	Contribution (%)
Length of Base, X_1	4	6m	30.2
Toe Extension, X_2	1	0.90m	14.5
Thickness of base, X_3	4	0.90m	5.3
Angle of front face, X_4 (%)	1	4.00	1.3
Angle of internal friction, Ø (°)	4	41	48.6
Expected maximum safety factor Fs (max) for this level			6.2
Found by numerical analysis maximum safety factor Fs (max)			6.7
Relative Error (%)			7.9

Table 7: Optimization results for maximum safety factor of overturning

Parameter	Level	Level Description	Contribution (%)
Length of Base, X_1	4	6m	64.6
Toe Extension, X_2	1	0.90m	7.6
Thickness of base, X_3	1	0.36m	2.9
Angle of front face, X_4 (%)	2	1.00	0.3
Angle of internal friction, Ø (°)	4	41	24.6
Expected maximum safety factor Fs (max) for this level			12.7
Found by numerical analysis maximum safety factor Fs (max)			12.9
Relative Error (%)			2.1

Table 8: Optimization results for maximum safety factor of slope stability

Parameter	Level	Level Description	Contribution (%)
Length of Base, X_1	4	6m	18.8
Toe Extension, X_2	1	0.90m	9.0
Thickness of base, X_3	4	0.90m	11.3
Angle of front face, X_4 (%)	4	4.00	2.2
Angle of internal friction, Ø (°)	4	41	58.7
Expected maximum safety factor Fs (max) for this level			3.0
Found by numerical analysis maximum safety factor Fs (max)			2.9
Relative Error (%)			3.3

In the results of optimization analyses of all safety factors, the length of base (X_1=4m), the toe extension (X_2=0.90m) and the angle of internal friction (Ø=41°) have same value for maximum value of safety factor. According to level description of parameters given in tables, numerical analyses have been repeated and safety factors has been obtained. Expected maximum safety factors have been compared with safety factors found by numerical analyses and the relative error has been gained. For safety factors of sliding, overturning and slope stability maximum relative error are respectively %7.9, %2.1 and %3.3.
The most effective parameter to safety factors of sliding and slope stability is the angle of internal friction that is respectively %48.6 and %58.7. The second effective parameter is the length of base, it is %30.2 for Fs (sliding) and is %18.8 for Fs (slope stability). Unlike other safety factors the most effective parameter for Fs (overturning) is the length of base with %64.6 and the second effective parameter is the angle of internal friction with %24.6.

4 Mathematical Model

In this study, the average S/N ratios have been employed to enhance the mathematical model for H=6m. Mathematical models valid for given lower-upper limits have been obtained by using average S/N ratios and parameter levels of design parameters. Each of them For calculation of Fs (sliding), Fs (overturning) and Fs (slope stability), mathematical model which is formed using different functions is given by Equation 4.

$$F_s = \sqrt{\frac{1}{10^{-\lambda/10}}} \tag{4}$$

Here, λ is total effect coefficient and it is given by Equation 5.

$$\lambda = \psi_B + \psi_{B_t} + \psi_d + \psi_m + \psi_\phi + \Delta \tag{5}$$

Here,
ψ_B : effect coefficient of the length of base, $X_1(H)$
ψ_{Bt} : effect coefficient of the toe extension, $X_2(X_1)$
ψ_d : effect coefficient of the thickness of base, $X_3(H)$
ψ_m : effect coefficient of the angle of front face, X_4
$\psi_Ø$: effect coefficient of the angle of internal friction, Ø
Δ : Coefficient of the average S/N ratio
Value of Δ which is changing in terms of calculation of Fs (sliding), Fs (overturning) and Fs (slope stability) are taken as respectively -1.034, 6.423 and 3.156. Detailed explanations of all effect coefficients of parameters are given in Table 9, Table 10 and Table 11 for different safety factors.

Table 9: The effect coefficients of parameters of Fs (sliding)

Lower-Upper Limits of Parameter	Mathematical Model
$0.25\ H \leq B \leq 1.00\ H$	ψ_B=$18.486B^3 - 42.672B^2 + 43.961B - 14.695$
$0.15B \leq B_t \leq 0.60B$	ψ_{B_t}= $28.534{B_t}^3 - 32.262{B_t}^2 - 0.1304B_t + 3.0854$
$0.06\ H \leq d \leq 0.15\ H$	ψ_d= $334.17d^3 - 39.307d^2 + 15.177d - 1.6215$
$0.00 \leq m \leq 0.02$	ψ_m= $1112.5m^2 - 47.793m + 0.2196$
$0.02 \leq m \leq 0.04$	ψ_m= $25.456m - 0.8004$
$20\ ^\circ \leq Ø \leq 41\ ^\circ$	ψ_ϕ= $23.23(\tan\phi)^3 - 51.682(\tan\phi)^2 + 67.598(\tan\phi) - 26.789$

Table 10: The effect coefficients of parameters of Fs (overturning)

Lower-Upper Limits of Parameter	Mathematical Model
$0.25\ H \leq B \leq 1.00\ H$	ψ_B= $31.275B^3 - 86.36B^2 + 98.437B - 33.259$
$0.15B \leq B_t \leq 0.60B$	$\psi_{B_{on}}$= $-6.1339{B_t}^3 - 4.6395{B_t}^2 - 0.0334B_t + 1.3126$
$0.06\ H \leq d \leq 0.15\ H$	ψ_d= $-226.44d^3 + 46.681d^2 - 12.536d + 1.0911$
$0.00 \leq m \leq 0.02$	ψ_m= $-675.06m^2 + 9.983m + 0.0187$
$0.02 \leq m \leq 0.04$	ψ_m= $1.5988m - 0.0836$
$20\ ^\circ \leq Ø \leq 41\ ^\circ$	ψ_ϕ=$-2.4364(\tan\phi)^3 + 1.584(\tan\phi)^2 + 15.801(\tan\phi) - 9.4873$

Table 11: The effect coefficients of parameters of Fs (slope stability)

Lower-Upper Limits of Parameter	Mathematical Model
$0.25\ H \leq B \leq 1.00\ H$	$\psi_B = -0.9481B^3 + 1.104B^2 + 3.1679B - 2.1271$
$0.15B \leq B_t \leq 0.60B$	$\psi_{B_{on}} = -0.0165{B_t}^3 - 1.1675{B_t}^2 - 1.80B_t + 0.8733$
$0.06\ H \leq d \leq 0.15\ H$	$\psi_d = -2336.4d^3 + 702.1d^2 - 48.723d - 0.118$
$0.00 \leq m \leq 0.02$	$\psi_m = -1202.6m^2 + 29.026m - 0.1358$
$0.02 \leq m \leq 0.04$	$\psi_m = 8.7062m - 0.2105$
$20\ ^\circ \leq Ø \leq 41\ ^\circ$	$\psi_\phi = 14.299(\tan\phi)^3 - 38.059(\tan\phi)^2 + 45.098(\tan\phi) - 16.095$

Safety factors of 1024 cantilever retaining wall designs which contain all value of five parameters with four levels have been obtained by both numerical analysis (Fs) and mathematical models (Fm). Belong to safety factors obtained from the numerical analysis and safety factors obtained from mathematical model, the relative error histograms for 1024 safety factors of sliding, overturning and slope stability are given respectively in Figure 6, Figure 7 and Figure 8. When histograms given in figures examine, it observes that they have approximately normal distribution.

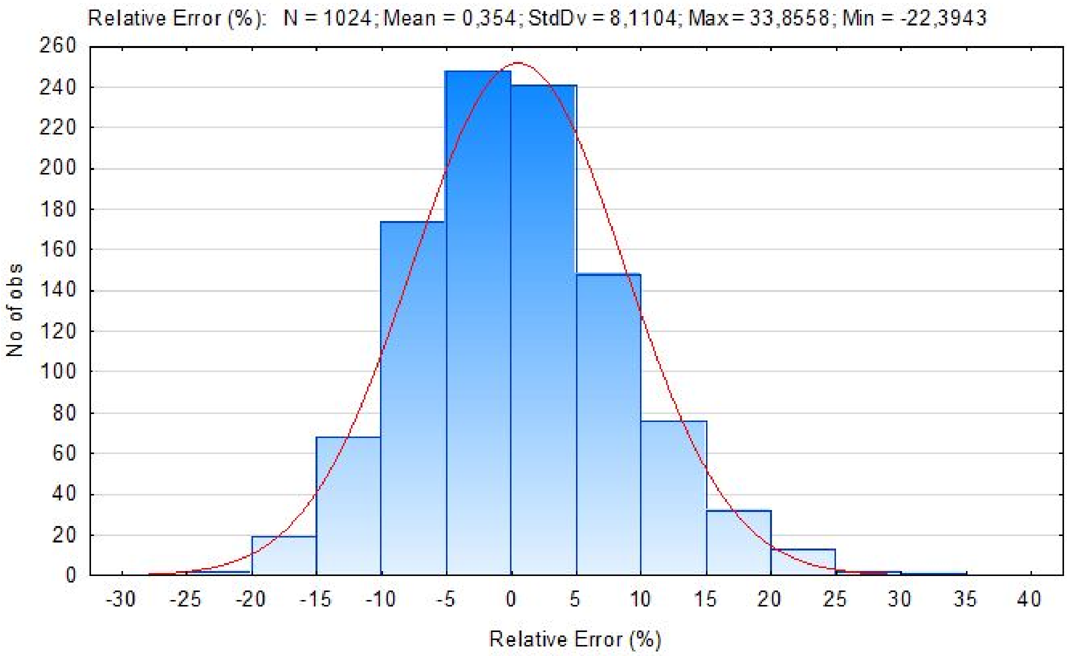

Figure 6: Distribution of relative error for safety factor of sliding

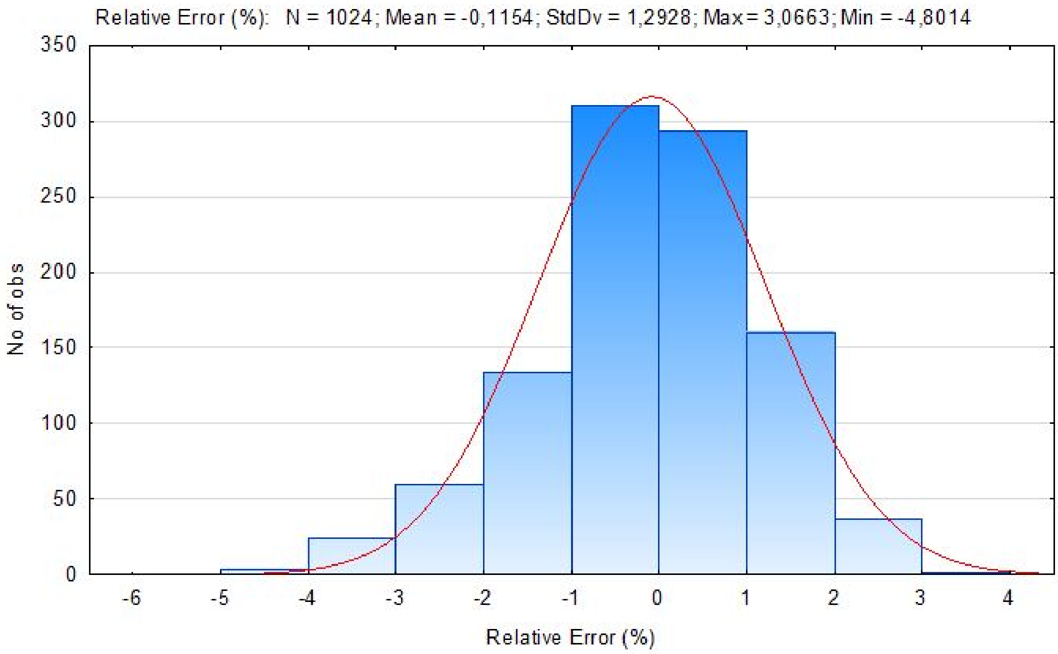

Figure 7: Distribution of relative error for safety factor of overturning

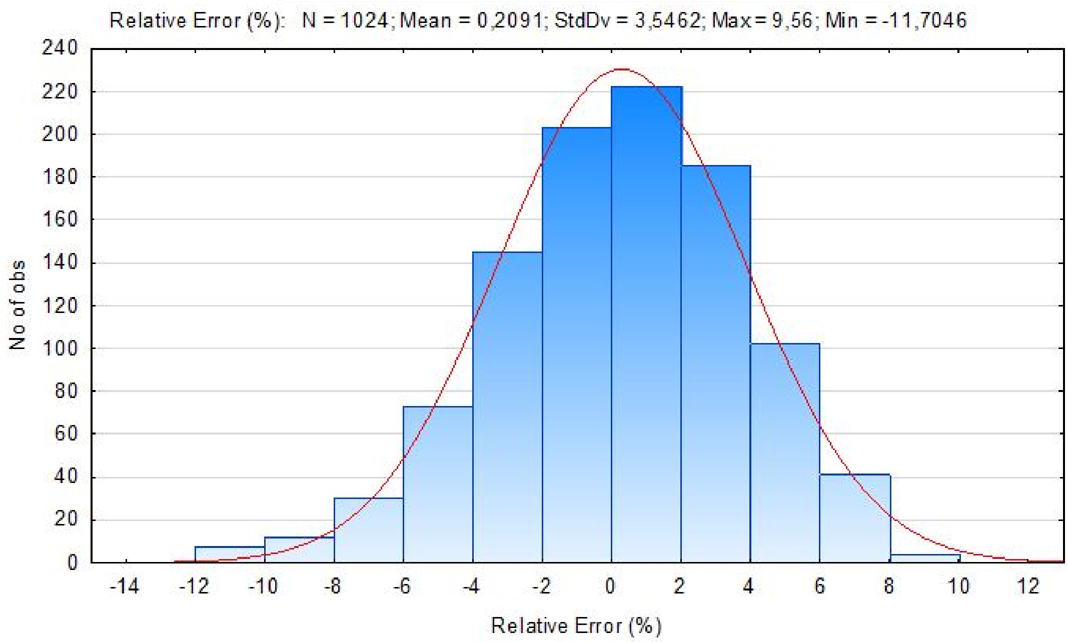

Figure 8: Distribution of relative error for safety factor of slope stability

5 Examples of Design of Cantilever Retaining Wall with Mathematical Model

To control for mathematical models of safety factors, design parameters which satisfy lower and upper limits previously mentioned of parameters have been selected randomly and 25 design have been formed by using these design parameters. All safety factors obtained from mathematical model (F_m) and numerical analyses (F_s) with randomly selected parameters are given in Table 12. The relative errors of safety factors of sliding, overturning and slope stability have been demonstrated by respectively Figure 9, Figure 10 and Figure 11.

6 Conclusions

In this study, mathematical model has been submitted used in safety factors of sliding, overturning and slope stability. In determination of models, Taguchi methods which is a one of the successful and favorable methods has been employed. Furthermore, the effects of parameters on the stability of the cantilever retaining wall have been investigated. Parameters of the length of base, the toe extension, the thickness of base, the angle of front face of wall and the angle of internal friction are taken as design parameters which have four levels each of them. By using L_{16} orthogonal design table suggested by Taguchi for fractional factorial design, 16 the cantilever retaining wall designs which formed according to L_{16} orthogonal design table have been analyzed in computer program and safety factors have been obtained. S/N, variance and optimization analyses have been performed by using safety factors obtained from numerical analyses. For determination of safety factors of sliding, overturning and slope stability, mathematical models have been formed by using average S/N ratios.

Results of the design of cantilever retaining wall with randomly selected 25 design parameters show that average absolute error is %4.8 for Fs(sliding), is %1.1 for Fs (overturning) and is %1.9 for Fs (slope stability). In 1024 designs of cantilever retaining wall with mathematical model, absolute relative errors of safety factors of sliding, overturning and slope stability are respectively %6.4, %1.0 and %2.8. When the cases are compared in terms of absolute relative error, it is observed that mathematical model derived from parameter levels may be used in determination of safety factors of sliding, overturning and slope stability even for except value of parameter levels.

The absolute relative errors obtained by using mathematical models, show that these models can be reliably used in calculation of safety factors of sliding, overturning and slope stability. Consequently, Taguchi Method can be employed in application of geotechnical engineering as an optimization technique. In future work, scope of the mathematical model can be widened for different wall height and different soil conditions.

Table 12: Results of design of cantilever retaining wall with design parameters selected randomly

No	Design Parameters					Sliding		Overturning		Slope stability	
	X_1 (H)	X_2 (X_1)	X_3 (H)	X_4 (%)	Ø (°)	F_s	F_m	F_s	F_m	F_s	F_m
1	0.30	0.20	0.07	0.011	22	0.29	0.28	0.53	0.52	0.87	0.87
2	0.35	0.22	0.10	0.039	37	1.15	1.23	1.23	1.22	1.81	1.80
3	0.45	0.50	0.13	0.022	35	0.96	0.89	1.49	1.48	1.65	1.68
4	0.65	0.40	0.10	0.031	40	2.25	2.16	4.34	4.42	2.10	2.15
5	0.90	0.55	0.11	0.012	24	0.65	0.61	3.65	3.61	1.16	1.19
6	0.80	0.35	0.10	0.025	25	0.82	0.74	3.65	3.60	1.28	1.25
7	0.40	0.44	0.14	0.034	26	0.42	0.43	0.85	0.84	1.16	1.19
8	0.55	0.28	0.08	0.028	37	1.62	1.57	3.03	3.05	1.84	1.81
9	0.95	0.24	0.13	0.036	30	1.74	1.77	6.35	6.26	1.78	1.82
10	0.60	0.26	0.07	0.018	33	1.29	1.18	3.12	3.12	1.62	1.56
11	0.70	0.42	0.10	0.026	28	0.84	0.76	2.98	3.00	1.35	1.35
12	0.39	0.34	0.13	0.038	21	0.29	0.31	0.73	0.72	0.93	0.95
13	0.85	0.17	0.13	0.035	31	1.83	1.81	5.43	5.35	1.84	1.87
14	0.45	0.45	0.08	0.013	38	1.17	1.13	1.90	1.90	1.73	1.72
15	0.92	0.56	0.07	0.024	32	1.17	1.12	5.37	5.29	1.54	1.53
16	0.28	0.19	0.10	0.038	23	0.29	0.32	0.46	0.45	0.95	0.98
17	0.37	0.43	0.11	0.025	36	0.90	0.87	1.15	1.14	1.64	1.66
18	0.42	0.56	0.08	0.032	29	0.43	0.43	1.00	0.99	1.17	1.15
19	0.96	0.28	0.14	0.022	34	2.49	2.37	7.41	7.31	2.08	2.13
20	0.36	0.31	0.07	0.032	21	0.27	0.26	0.69	0.67	0.83	0.82
21	0.28	0.38	0.14	0.014	38	1.00	0.95	0.73	0.73	1.81	1.86
22	0.77	0.54	0.11	0.027	23	0.51	0.48	2.60	2.59	1.06	1.08
23	0.56	0.53	0.10	0.034	35	1.03	1.00	2.28	2.33	1.61	1.64
24	0.82	0.59	0.14	0.039	22	0.48	0.50	2.56	2.53	1.05	1.11
25	0.43	0.28	0.07	0.024	39	1.47	1.49	2.07	2.04	1.84	1.82

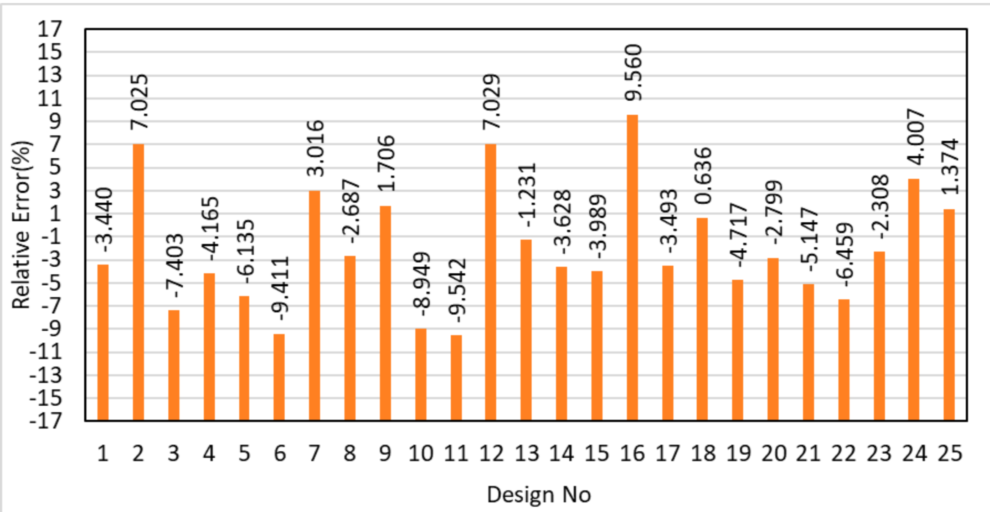

Figure 9: Relative error of randomly selected design parameters for Fs (sliding)

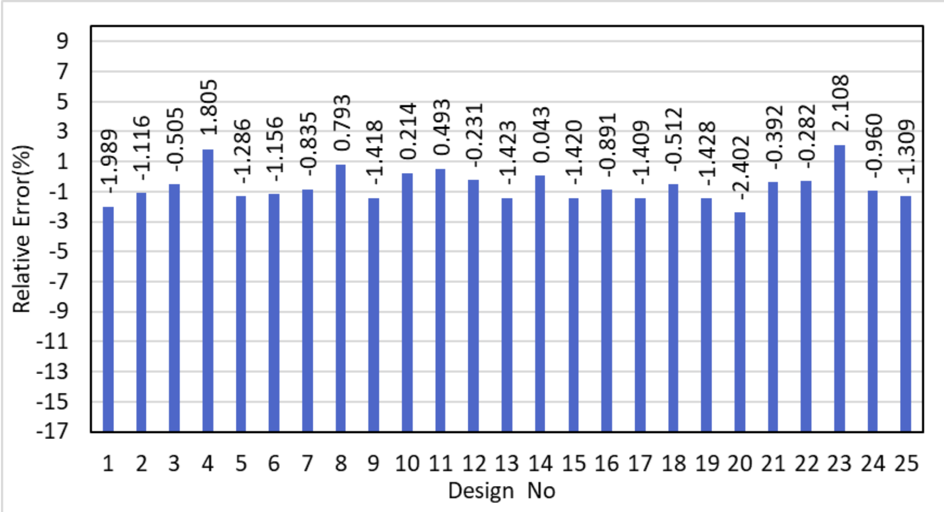

Figure 10: Relative error of randomly selected design parameters for Fs (overturning)

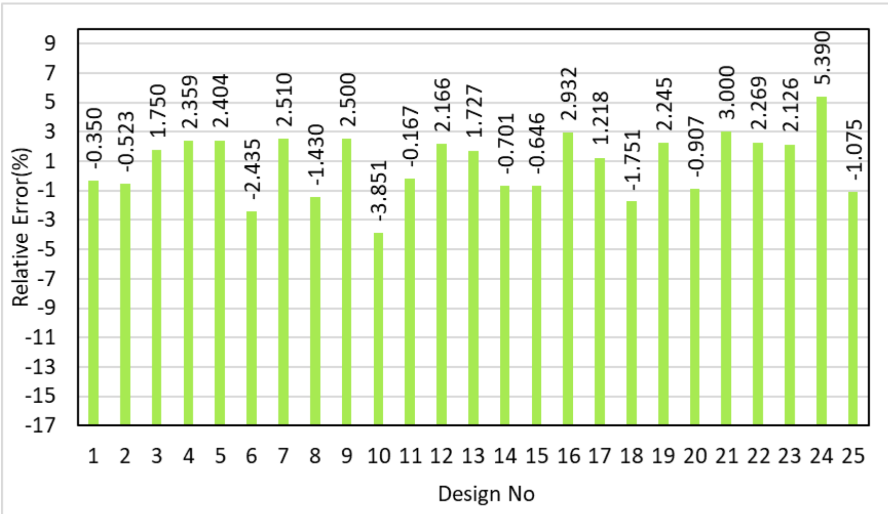

Figure 11: Relative error of randomly selected design parameters for Fs (slope stability)

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