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Investigation of Design Criteria for the Type of Gabion Walls

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ABSTRACT

In civil engineering, connecting two different levels each other to provide the essential safety is a common problem and in solving this problem retaining structures are widely used. In this study, the design criteria of gabion retaining wall which is a kind of retaining wall was investigated by using Taguchi Method. Parameters which affect the design of gabion retaining wall are height, length of base, wall angle and angle of internal friction and slope of backfill and 16 different Taguchi design tables were formed by these using parameters. These design tables were modelled by using computer program and analyzed. As a result of computer analyses, safety factors of sliding and overturning of gabion wall and tensile strength of gabion basket wire mesh were obtained. By using the computer analysis results, "S/N, Signal/Noise", "Variance" and "Optimization" analyses were made for each Taguchi design. According to result of these analyses, parameters effective in the design of gabion retaining wall and design values which have maximum and minimum safety factor was determined.

Keywords: Design Criteria, Gabion Structures, Gabion Retaining Wall, Retaining Structures, Taguchi Method

1. INTRODUCTION

Gabion is originally an Italian word which means big cage. Gabion basket is a rectangular cage obtained from hexagonal double-twisted and zinc coated steel wire mesh and filled with stone or rock of certain size and mechanical characteristics. Gabion structures are built by placing these baskets in a specific order and these structures are used in many application of civil engineering like retaining wall in highways, railway, erosion prevention, slope stability, stream bed improvement, shoreline survey, bridge approach etc.

At early 5000 B.C. gabion walls were used for coastal protection along Nile River in Egypt and then in 1000 B.C. it was similarly used along Yellow River by Chines. In history we can see other applications like using gabion wall as temporary wall for military purpose by Julius Caesar and as foundations of the San Marco Castle in Milan by Leonardo da Vinci. The first time patent of gabion basket was taken by Gaetano Maccaferri in the late 1800s and was used as first gabion wall in Reno River in 1893.

To study the behavior and strength of gabion structure under loads, analytical and numerical analyses and laboratory and field test have been made. The first experimental study in the literature has been made by the company of Maccaferri [1]. Engineering behavior of gabion basket which uses as retaining wall has been investigated by [2, 3, 4, and 5]. Studies about usage of gabion baskets for different purposes [6, 7, 8, 9, 10, 11] show that it is practical solution for many types of engineering problems.

2. ANALYSIS OF WORKS

In recent years, statistical methods have been developed since investigating parameters effect on performance requires a long time and many analyses. Taguchi is one of these methods which make it possible to get results in short time and with less number of analyses.

2.1. Taguchi Method and Computer Analyses

Taguchi is a method which minimizes the effects of uncontrollable factors and limits number of analyses by using orthogonal arrays. In Taguchi Method, result is evaluated by calculating Signal/Noise (S/N) ratio of data obtained from the analysis.

In Taguchi Method, selection of orthogonal array is carried out according to number of level and total degree of freedom. General representation of orthogonal array is $Ld_{(a)}^{k}$ or Ld. Here d is the total number of analysis, a is the number of level of parameters, k is number of parameters and L demonstrates orthogonal array. According to Taguchi Method parameters affecting the results are divided into two groups, controllable and uncontrollable parameters.

In the study uncontrollable parameters;

- Gabion filling unit weight: γg= 20 kN/m3
- Gabion filling angle of internal friction: Ø= 30°
- Gabion filling cohession: cg= 0
- Gabion basket tensile strength of wire mesh: Rt= 50 kN/m
- Gabion basket height: hg= 1 m
- Backfill unit weight: γk= 18 kN/m3
- Backfill cohession: c= 0
- Friction angle between wall and soil: δ= 10°
- Bearing capacity of soil of foundation: Rd=250 kN/m2

In the study controllable parameters;

- Gabion retaining wall height (H): 4 m, 6 m, 8 m and 10 m
- Gabion retaining wall length of base (B): 0, 30 H, 0, 45 H, 0, 60 H and 0, 75 H
- Angle of internal friction of backfill (Ø): 15°, 25°, 35° and 45°
- Gabion retaining wall angle (α): 0°, 4°, 8° and 12°
- Slope of backfill (β): 0°, 5°, 10° and 20°

After determining controllable and uncontrollable parameters the number of levels is defined. In this study, parameters level has been defined as four which is a function associated with the degree of freedom. For four-level parameter, degree of freedom is three and for five controllable parameters total degree of freedom is fifteen (3x5=15). The number of experiment of orthogonal array must be selected greater than fifteen and it can be selected as sixteen (15+1=16) which should be the smallest orthogonal array. In this case, the smallest orthogonal array is L_{16} $(4)^{5}$ and full factorial experimental design which consists of four levels and five number of parameters is performed. The number of analysis is 4^5 =1024 and instead of 1024, 16 designs have been made by using L_{16} orthogonal array. In Table 1, controllable parameters which are arranged according to Taguchi are given. 16 different computer modeling analyses were conducted according to these parameters and safety factors were obtained by using computer analyses (Table 1).

Table 1. Taguchi orthogonal index table and computer analysis results

Design No	According to Taguchi Method revised controllable parameters					Result of computer analysis				
						Fs (Sliding)	Fs (Overturning)	Fs (Tensile strength of gabion basket)		
	H (m)	B (m)	Ø (°)	α (°)	β (°)			1	2	3
1	4	1,20	15	0	0	0,298	0,441	0,02	2,22	7,18
2	4	1,80	25	4	5	0,9	1,276	2,06	3,73	7,84
3	4	2,40	35	8	10	2,866	4,744	3,39	4,87	8,05
4	4	3,00	45	12	20	10,832	23,303	3,62	5,04	8,33
5	6	1,80	25	8	20	0,436	0,531	0,02	0,02	1,19
6	6	2,70	15	12	10	0,28	1,029	0,66	0,95	1,66
7	6	3,60	45	0	5	5,21	3,476	1,9	2,37	3,11
8	6	4,50	35	4	0	3,722	6,042	2,1	2,61	3,41
9	8	2,40	35	12	5	1,523	1,53	1,3	1,5	1,85
10	8	3,60	45	8	0	4,826	3,541	1,65	1,91	2,27
11	8	4,80	15	4	20	0,252	0,791	0,08	0,12	0,18
12	8	6,00	25	0	10	1,295	2,378	1,24	1,49	1,82
13	10	3,00	45	4	10	2,218	0,84	0,63	0,58	0,41
14	10	4,50	35	0	20	1,16	0,757	0,62	0,69	0,76
15	10	6,00	25	12	0	1,306	3,919	1,24	1,4	1,61
16	10	7,50	15	8	5	0,587	3,239	1,05	1,21	1,42

2.2. Signal/Noise (S/N), Variance and Optimization Analyses

In this study, by using safety factors obtained by computer analysis Signal/Noise (S/N), variance and optimization analyses were carried out. Signal/Noise ratio which is defined by Taguchi is analysis to minimize effect of controllable parameters on result. In this study, calculating of S/N ratio was performed according to the target state of “bigger is better” (1). Variance analysis was conducted to determine effect of the parameters in the design of gabion retaining wall. Optimization analysis determines parameter levels and values which make maximum and minimum safety factors. These analyses were applied for safety factors of sliding, overturning and tensile strength of gabion basket wires.

$$S / N \text{ ratio} = -10 \log[\sum (1 / Y^2) / n] \qquad (1)$$

3. RESULTS AND DISCUSSION

In the design of gabion wall, S/N, variance and optimization analyses were made according to Taguchi Method to determine some parameters like height (H), length of base due to height (B), wall angle (α), angle of internal friction (ϕ) and slope of backfill (β) effect on safety factors of sliding, overturning and tensile strength of gabion basket wire mesh.

3.1. S/N Analyses

Table 2. S/N ratio for check for sliding, overturning and tensile strength of gabion basket

Design No	Check for sliding S/N ratio	Check for overturning S/N ratio	Check for tensile strength S/N ratio		
			1	2	3
1	-10,46	-7,11	6,0	46,9	57,1
2	-0,92	2,12	46,3	51,4	57,9
3	9,16	13,52	50,6	53,8	58,1
4	20,69	27,35	51,2	54,1	58,4
5	-7,13	-5,50	6,0	6,0	41,5
6	-11,06	0,25	36,4	39,5	44,4
7	14,34	10,82	45,6	47,5	49,9
8	11,41	15,62	46,4	48,3	50,7
9	3,64	3,69	42,3	43,5	45,3
10	13,68	10,98	44,4	45,6	47,1
11	-12,04	-2,04	18,1	21,6	25,1
12	2,28	7,52	41,9	43,5	45,2
13	6,93	-1,51	36,0	35,3	32,3
14	1,29	-2,42	35,9	36,8	37,6
15	2,35	11,86	41,9	42,9	44,1
16	-4,58	10,21	40,4	41,7	43,0
Average S/N Ratio	2,47	5,96	36,8	41,1	46,1

In Table 2, S/N ratio values which are calculated by using Fs (Table 1) and average S/N ratios corresponding to each parameter level are given (Table 3).

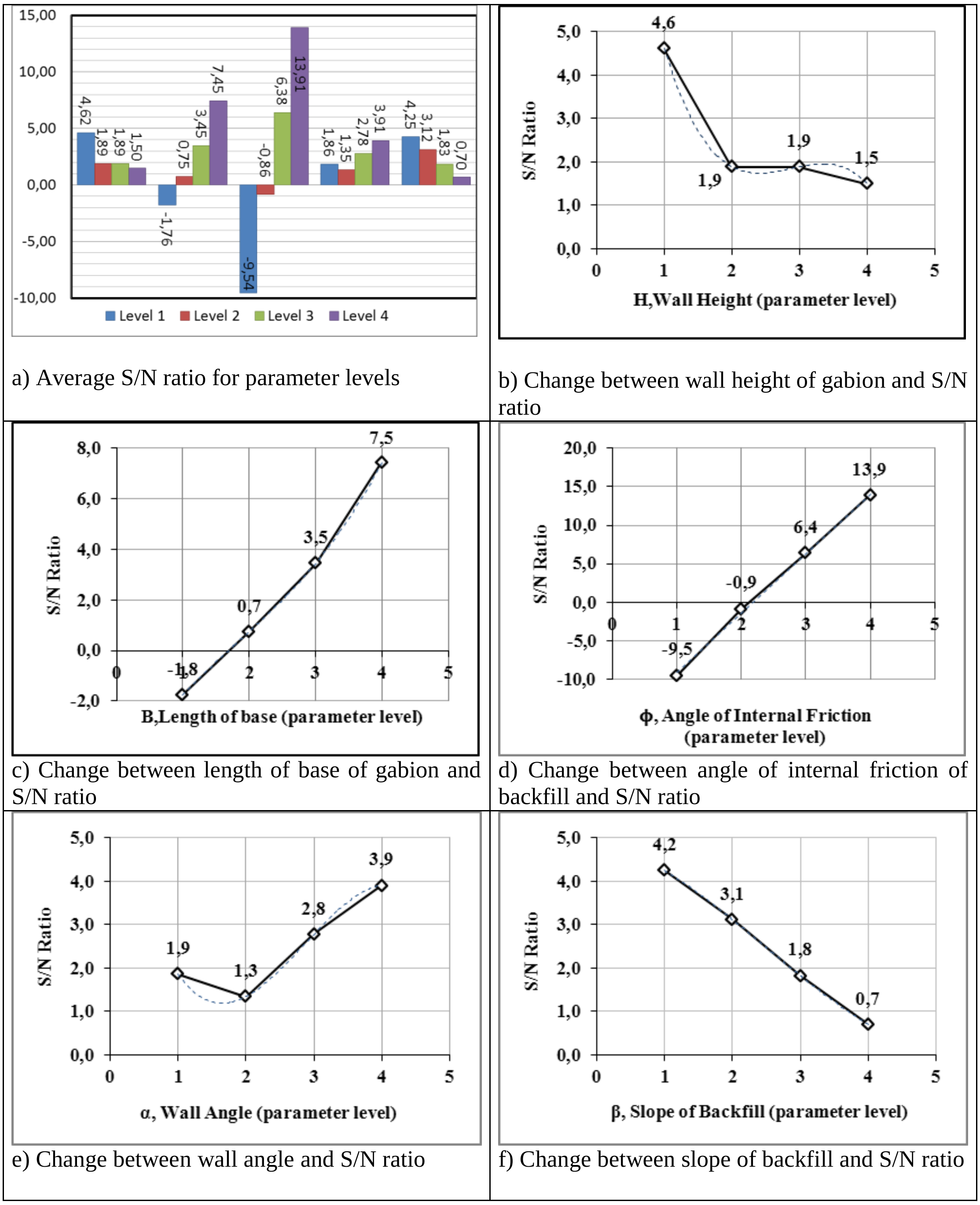
Table 3. Average S/N ratio for parameter levels

<table>
<tr><th rowspan="2"></th><th rowspan="2">Parameter</th><th colspan="12">S/N Ratio</th></tr>
<tr><th colspan="3">Level 1</th><th colspan="3">Level 2</th><th colspan="3">Level 3</th><th colspan="3">Level 4</th></tr>
<tr><td rowspan="6">Check for sliding</td><td>Wall Height (H)</td><td colspan="3">4,62</td><td colspan="3">1,89</td><td colspan="3">1,89</td><td colspan="3">1,50</td></tr>
<tr><td>Length of Base (B)</td><td colspan="3">-1,76</td><td colspan="3">0,75</td><td colspan="3">3,45</td><td colspan="3">7,45</td></tr>
<tr><td>Angle of Internal Friction (Ø)</td><td colspan="3">-9,54</td><td colspan="3">-0,86</td><td colspan="3">6,38</td><td colspan="3">13,91</td></tr>
<tr><td>Wall Angle (α)</td><td colspan="3">1,86</td><td colspan="3">1,35</td><td colspan="3">2,78</td><td colspan="3">3,91</td></tr>
<tr><td>Slope of Backfill (β)</td><td colspan="3">4,25</td><td colspan="3">3,12</td><td colspan="3">1,83</td><td colspan="3">0,70</td></tr>
<tr><td>Average S/N</td><td colspan="12">2,47</td></tr>
<tr><td rowspan="6">Check for overturning</td><td>Wall Height (H)</td><td colspan="3">8,97</td><td colspan="3">5,30</td><td colspan="3">5,04</td><td colspan="3">4,53</td></tr>
<tr><td>Length of Base (B)</td><td colspan="3">-2,61</td><td colspan="3">2,73</td><td colspan="3">8,54</td><td colspan="3">15,18</td></tr>
<tr><td>Angle of Internal Friction (Ø)</td><td colspan="3">0,33</td><td colspan="3">4,00</td><td colspan="3">7,61</td><td colspan="3">11,91</td></tr>
<tr><td>Wall Angle (α)</td><td colspan="3">2,20</td><td colspan="3">3,55</td><td colspan="3">7,30</td><td colspan="3">10,79</td></tr>
<tr><td>Slope of Backfill (β)</td><td colspan="3">7,84</td><td colspan="3">6,71</td><td colspan="3">4,95</td><td colspan="3">4,35</td></tr>
<tr><td>Average S/N</td><td colspan="12">5,96</td></tr>
<tr><td rowspan="6">Check for tensile strength of gabion basket</td><td>Gabion Basket Layer No</td><td>1</td><td>2</td><td>3</td><td>1</td><td>2</td><td>3</td><td>1</td><td>2</td><td>3</td><td>1</td><td>2</td><td>3</td></tr>
<tr><td>Wall Height (H)</td><td>38,5</td><td>51,5</td><td>57,9</td><td>33,6</td><td>35,5</td><td>46,6</td><td>36,6</td><td>38,5</td><td>40,7</td><td>38,5</td><td>39,2</td><td>39,3</td></tr>
<tr><td>Length of Base (B)</td><td>22,6</td><td>32,9</td><td>44,1</td><td>40,7</td><td>43,4</td><td>46,8</td><td>39,0</td><td>41,4</td><td>44,3</td><td>45,0</td><td>46,9</td><td>49,3</td></tr>
<tr><td>Angle of Internal Friction (Ø)</td><td>25,2</td><td>37,4</td><td>42,4</td><td>34,0</td><td>36,0</td><td>47,2</td><td>43,8</td><td>45,6</td><td>47,9</td><td>44,3</td><td>45,6</td><td>46,9</td></tr>
<tr><td>Wall Angle (α)</td><td>32,3</td><td>43,7</td><td>47,4</td><td>36,7</td><td>39,2</td><td>41,5</td><td>35,3</td><td>36,8</td><td>47,4</td><td>42,9</td><td>45,0</td><td>48,1</td></tr>
<tr><td>Slope of Backfill (β)</td><td>34,7</td><td>46,0</td><td>49,8</td><td>43,6</td><td>46,0</td><td>49,0</td><td>41,2</td><td>43,0</td><td>45,0</td><td>27,8</td><td>29,6</td><td>40,7</td></tr>
</table>

In figure 1, graphical representation of average S/N ratio (a) and change between S/N and the parameters are given for sliding check. As the height of the gabion wall increases, safety factor of sliding reduces (b). As wall height due to length of base increases, safety factor of sliding increases rapidly (c) and similar situation seems for angle of internal friction (d). As seen change between wall angle and S/N ratio, safety factor of sliding decreases up to second level (α=4°) and then increases (e). As slope of backfill increases, safety factor of sliding decreases (f).

In figure 2, graphical representation of average S/N ratio (a) and change between S/N and the parameters is given for overturning check. As wall height of gabion wall increase, safety factor of overturning reduces alike for sliding check (b). As length of base due to height increases, safety factor against overturning increases fast and close to linear (c) and similar situation also seems approximately for angle of internal friction (d). As seen change between wall angle and S/N ratio, safety factor of overturning decreases up to second level (α=4°) and then increases (e). As slope of backfill increases, safety factor of overturning decreases (f).

In figure 3, change between S/N ratio and the parameters is given for check tensile strength of gabion basket wire mesh. Generally, when change between wall height and S/N ratio examined, reduction in tensile strength observed with increasing wall height (a). In designs, as length of base due to height increase, tensile strength of gabion basket shows increase (b). Similar behavior seems for angle of internal friction (c). As wall angle increases, tensile strength of gabion basket wire mesh shows generally increases (d). As slope of backfill increases, tensile strength of gabion basket wire mesh decreases (e).



a) Average S/N ratio for parameter levels

b) Change between wall height of gabion and S/N ratio

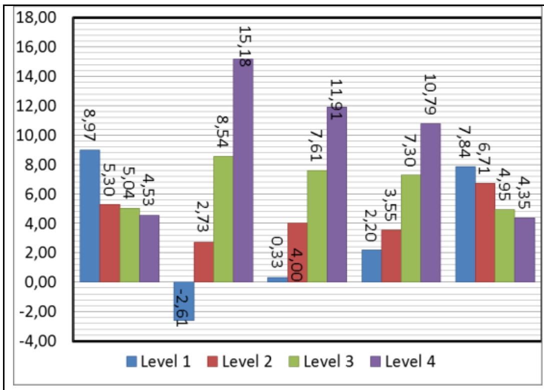
c) Change between length of base of gabion and S/N ratio

d) Change between angle of internal friction of backfill and S/N ratio

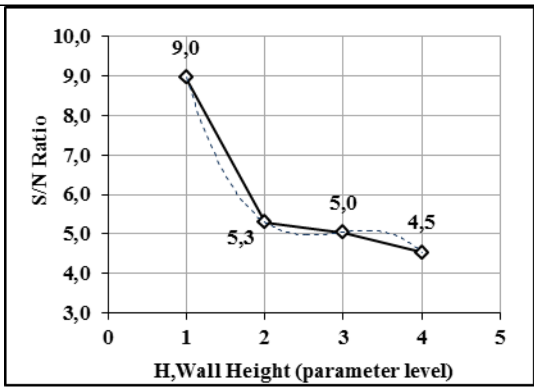
e) Change between wall angle and S/N ratio

f) Change between slope of backfill and S/N ratio

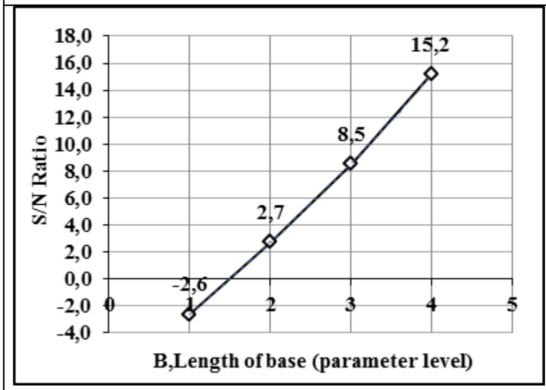
Figure 1. Change between S/N ratio and parameters for check for sliding



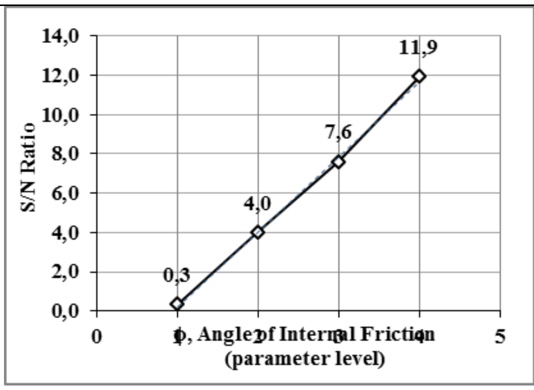
a) Average S/N ratio for parameter levels



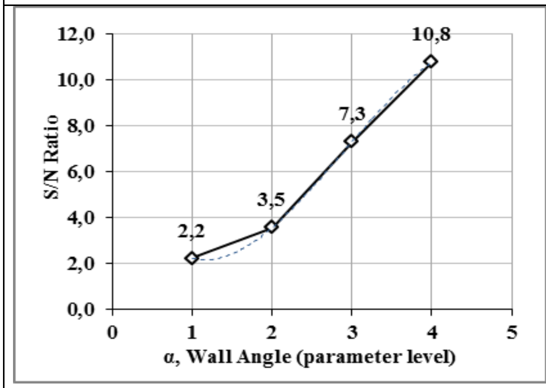
b) Change between wall height of gabion and S/N ratio



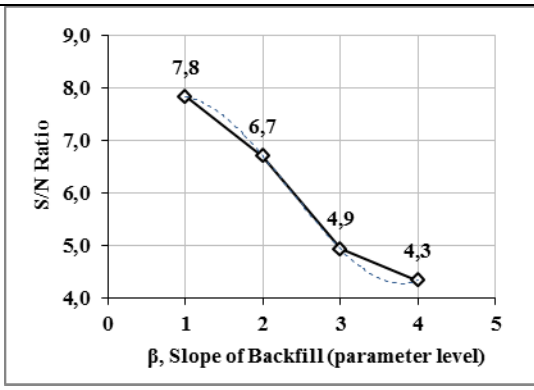
c) Change between length of base of gabion and S/N ratio



d) Change between angle of internal friction of backfill and S/N ratio



e) Change between wall angle and S/N ratio



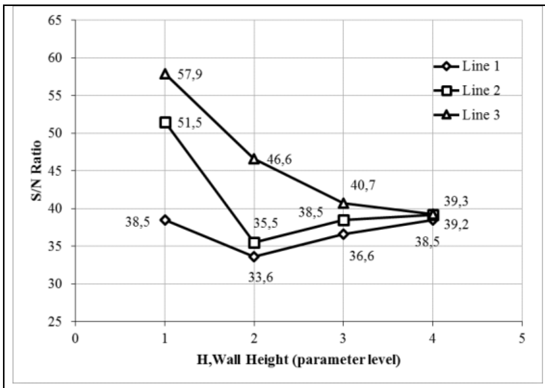
f) Change between slope of backfill and S/N ratio

Figure 2. Change between S/N ratio and parameters for check for overturning

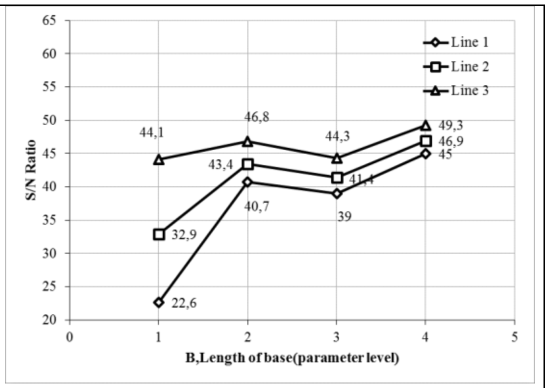
3.2. Variance Analyses

Multivariate analysis of variance (ANOVA) were conducted to determine effect of the parameters which are H, B, Ø, α and β on safety factors of sliding and overturning and tensile strength of wire mesh of gabion basket (Table 4).

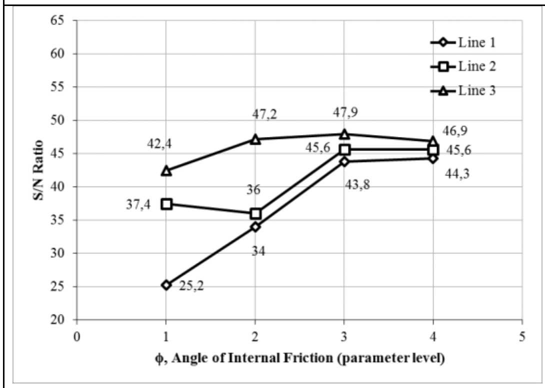
As can be seen from the results of analysis of variance, the most effective parameter on safety factor of sliding is angle of internal friction (ϕ) (82, 5%) and secondary parameter is length of base (B) (12, 9%). The most effective parameter on safety factor of overturning is length of base (B) (55, 8%) and secondary parameter is angle of internal friction (ϕ) (23, 5%). The most effective parameter on tensile strength of wire mesh of gabion basket in first row is length of base (B)(37, 9%) and secondary parameter is angle of internal friction (ϕ) (32, 3%). The most effective parameter on tensile strength of wire mesh of gabion basket in second row is slope of backfill (β) (32, 4%) and secondary parameter is wall height (H) (26, 9%). The most effective parameter on safety factor against tensile strength of wire mesh of gabion basket in third row is wall height (H) (64, 4%) and secondary parameter is slope of backfill (β) (15, 8%).



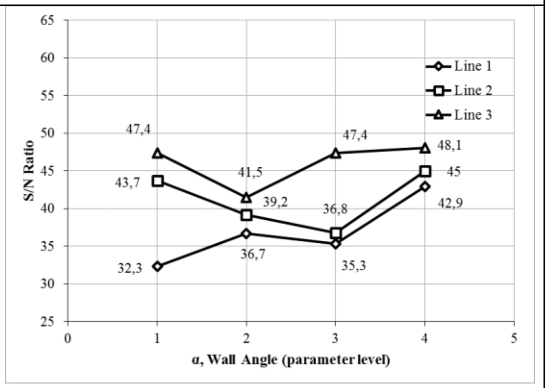
a) Change between wall height of gabion and S/N ratio



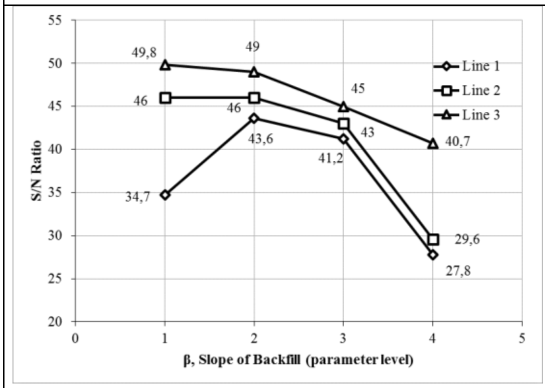
b) Change between length of base of gabion and S/N ratio



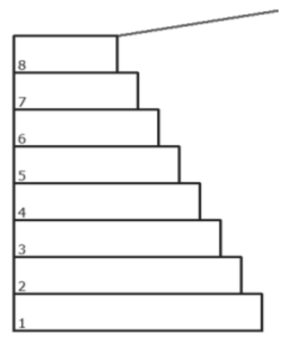
c) Change between angle of internal friction of backfill and S/N ratio



d) Change between wall angle and S/N ratio



e) Change between slope of backfill and S/N ratio



f) Gabion basket rows of gabion wall (H=8 m)

Figure 3. Change between S/N ratio and parameters for check for tensile strength S/N ratio

3.3. Optimization analyses

Optimization analyses were conducted to determine parameter levels and values of maximum and minimum of safety factors of sliding and overturning and tensile strength of wire mesh of gabion basket. Optimal parameter levels and values according to results of analyses were given for maximum and minimum safety factors in Table 5.

Table 4. Results of analysis of variance

	Parameter	Degree of Freedom (DOF)	Sum of Squares (Ss)	Variance	Percent (P) (%)
Check for sliding	Wall Height (H)	3	25,4	8,5	1,7
	Length of Base (B)	3	187,8	62,6	12,9
	Angle of Internal Friction (Ø)	3	1202,2	400,7	82,5
	Wall Angle (α)	3	14,9	5,0	1,0
	Slope of Backfill (β)	3	27,2	9,1	1,9
	Total	15	1457,5		100
Check for overturning	Wall Height (H)	3	49.3	16,4	4,0
	Length of Base (B)	3	702,1	234,0	55,8
	Angle of Internal Friction (Ø)	3	295,0	98,3	23,5
	Wall Angle (α)	3	180,1	60,0	14,3
	Slope of Backfill (β)	3	30,8	10,3	2,4
	Total	15	1257,3		100

		Gabion Basket Layer No	1	2	3	1	2	3	1	2	3
Check for tensile strength of gabion basket	Wall Height (H)	3	64.7	609.3	860.4	21.6	203.1	286.8	2.1	26.9	64.4
	Length of Base (B)	3	1158.0	420.7	73.0	386.0	140.2	24.3	37.9	18.5	5.5
	Angle of Internal Friction (Ø)	3	986.1	321.6	75.0	328.7	107.2	25.0	32.3	14.2	5.6
	Wall Angle (α)	3	238.7	177.9	115.7	79.6	59.3	38.6	7.8	7.8	8.7
	Slope of Backfill (β)	3	608.8	734.1	211.2	202.9	244.7	70.4	19.9	32.4	15.8
	Total	15	3056.1	2263.7	1335.2				100	100	100

Table 5. Maximum and minimum parameters levels and values

	Maximum			Minimum		
	Parameter	Level	Level description	Parameter	Level	Level description
Check for sliding	H	1	4m	H	4	10m
	B	4	0.75H	B	1	0.30H
	Ø	4	45°	Ø	1	15^0
	α	4	12°	A	2	4^0
	β	1	0°	B	4	20^0
	Expected maximum safety factor Fs (max) for this level		16.28	Expected minimum safety factor Fs (min) for this level		0.13
	Found by verification analysis maximum safety factor Fs (max)		12.63	Found by verification analysis minimum safety factor Fs (min)		0.10
Check for overturning	H	1	4m	H	4	10m
	B	4	0.75H	B	1	0.30H
	Ø	4	45^0	Ø	1	15^0
	α	4	12^0	α	1	0
	β	1	0^0	β	4	20^0
	Expected maximum safety factor Fs (max) for this level		34.8	Expected minimum safety factor Fs (min) for this level		0.18
	Found by verification analysis maximum safety factor Fs (max)		27.17	Found by verification analysis maximum safety factor Fs (min)		0,11

Check for tensile strength of gabion basket	Layer No	1	2	3	1	2	3	1	2	3	1	2	3
	H	4	1	1	10m	4m	4m	1	2	3	6m	6m	10m
	B	4	4	4	0.75H	0.75 H	0.75H	2	2	4	0.3 H	0.3H	0.3H
	Ø	4	4	3	45^0	45^0	35^0	1	1	1	15^0	25^0	15^0
	α	4	4	4	12^0	12^0	12^0	1	2	1	0^0	4^0	4^0
	β	2	2	1	5°	0°	0°	1	3	2	20^0	20^0	20^0

4. CONCLUSION

In this study, effects of parameters on design criteria of gabion retaining wall has been investigated by using Taguchi Method which is one of the strongest optimization technique. Parameters which affect the design of gabion retaining wall are height, length of base, wall angle and angle of internal friction and slope of backfill. According to Taguchi Method by using L_{16} orthogonal array which consist of four levels and five parameters 16 different designs were modeled and analyzed by computer program to obtain safety factors of sliding and overturning and tensile strength of gabion basket wire mesh. “S/N, “Variance” and “Optimization” analyses were performed by using results gained from computer analyses.

S/N analyses show that the safety factors of sliding and overturning has an indirect proportion relationship with increasing of wall height (H) and slope of backfill (β), and directly proportional with increasing of length of base (B), angle of friction (ϕ) and wall angle (α). The results show that change between safety factors of sliding and overturning are similar with increase of parameters level. While checking tensile strength of gabion basket wire mesh, change between S/N ratio and the parameters is generally similar to the behavior of sliding and overturning.

In variance analyses, effect rate of wall height (H) being low shows that selection of base of length as B= 0.30H- 0.75H is reasonable for all verification. As can be seen from the results of analysis of variance, the most effective parameter on safety factor of sliding is angle of internal friction (ϕ) (82,5%) and secondary parameter is length of base (B) (12,9%). The most effective parameter on safety factor of overturning is length of base (B) (55, 8%) and secondary parameter is angle of internal friction (ϕ) (23, 5%). The most effective parameter on safety factor against tensile strength of wire mesh of gabion basket in third row is wall height (H) (64, 4%) and secondary parameter is slope of backfill (β) (15, 8%). The most challenging part of the wire mesh of gabion basket is first row and tensile strength in this row is highest.

As a result of optimization analysis and generally using B = 0.75H, Ø = 45°, α = 12°, β = 0° parameters for the maximum safety factor and B = 0.30H, Ø = 15°, α = 0°, β = 20° parameters for the minimum safety factor in design has been obtained for all verification. The maximum and minimum safety factor for wall height has not been defined it is because the length of base is depended on the wall height (0.30H, 0.45H, 0.60H, 0.75H). The results show that maximum and minimum values of tensile strength of gabion basket wire mesh are unreasonable.

In this study, prediction and optimization analyses which was made by using Taguchi Method for safety factors of sliding and overturning of gabion wall and tensile strength of gabion basket wire mesh, show that results obtained from these analyses is close to real value. Consequently, Taguchi Method can be used in application of geotechnical engineering as an optimization technique.

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