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# Application of Taguchi method in optimization of soil-nailed excavation design

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## ABSTRACT

One of the most common ways for temporary stabilizing deep excavations is soil nailing. In comparison with other excavation stabilizing methods, this method is relatively expensive. Therefore, it is important to use an economical design in soil-nailed excavations. Each economical design must satisfy safety and displacement obligations in order to limit excavation displacements to allowable amounts as well as providing stability safety factors. Effective parameters in soil-nailed excavations are mechanical parameters of soil, bar length and diameter, drillhole diameter, vertical and horizontal space of bars, shotcrete strength and thickness in one hand, and allowable displacements of wall, stability safety factors, nail pull-out strength, and nail tensile strength according to selected code in the other hand. Due to plurality of effective parameters in design of soil-nailed excavations, using a systematic method to select an optimum design is economically worthy. In this paper, optimization of design was carried out with Taguchi method. In this method, the numerical analyses are reduced to limited numbers based on an orthogonal array, in each analysis a certain value is assigned to each effective factor. Analyses were accomplished by finite element code; PLAXIS V 8.5. According to objective function which is total cost, an optimum design for two excavation depths of 15 and 20 m in both clayey and sandy soils are obtained.

*Keywords:* excavation, soil nailing, optimization, Taguchi method

## 1 INTRODUCTION

The French national research project CLOUTERRE carried out a comprehensive study on soil-nailed walls in the years of 1980s. In this project, the effect of layout of nails on the stability of soil-nailed structures was discussed qualitatively. According to this study, installation of longer nails into the upper level of walls found to work well for very tall walls. This type of layout contributes more toward reducing tilting and lateral displacement at the wall facing. Jewell (1980) conducted a series of laboratory direct shear tests to investigate the effect of orientation of flexible nails on increase of shear resistance at failure in soil mass. To mobilize the maximum shear resistance in soil mass, the optimal direction of nails with respect to the normal of shear surfaces found to be approximately 30°. Sabhahit et al. (1995) indicated that the total amount of required length of nails decreases if nails are placed in the lower part of slope. Based on the limit equilibrium analysis, they suggested that horizontal placement of nails is the optimal direction except for the lower-most nails. Shafiee (1986) conducted a research on the effect of nail's orientation on deformation of soil-nailed walls using finite element method. The walls with nails inclined at 0° and 30° with respect to the horizontal line were analysed. He found that deformation of wall face with nails inclined at 30° is greater than that for nails placed horizontally. Based on experimental studies, Marchal (1984) indicated that the orientation of nails with respect to the failure surface in soil mass plays a role in the mobilization of tensile and shear forces in nails as well as in the overall shear resistance of nail-reinforced soils. Jones (1990) suggested that nails can be placed with a slightly upward inclination at the upper level and inclined gradually downward at the lower level of slopes in order to develop primarily tensile forces in nails and to reach the optimal condition. Chia-Cheng Fan (2008) showed that the effect of vertical spacing of nails on overall stability of excavations is negligible, if the number of nails remains constant.

Most of the above-mentioned researches regarding the effect of orientation and geometric layout of nails are focused on the overall stability of retaining structures. In some cases, internal failure of retaining structures may cause local failure which can increase possibility of overall failure. Therefore, it is important to consider both internal and external stability in an appropriate design of nails. In this paper, optimization of soil-nailed excavations was carried out by Taguchi method in which effective parameters can be changed systematically. The variables considered in Taguchi method are horizontal spacing of nails, bar size (length and diameter), shotcrete thickness and drillhole diameter.

## 2 TAGUCHI METHOD

Dr. Genichi Taguchi developed a statistical method to improve the quality of manufactured goods, and more recently also applied to engineering, biotechnology, marketing and advertising.

This method is based on orthogonal arrays (OA) which provide a set of well balanced (minimum) experiments allowing significant reduction in the number of experimental runs to find the optimal solution. Signal-to-Noise ratios (S/N), which are log functions of desired output, serve as objective functions for optimization, help in data analysis and prediction of optimum results. These are used to allow the control of the response as well as to reduce the variability about the response. The use of ANOVA (analysis of variance) is to calculate the statistical confidence associated with the conclusions drawn. The optimization involves determining the best control factor levels so that the output is at the target value. In this method, the word "optimization" implies "determination of best levels of control factors".

The major steps of implementing the Taguchi method are: (1) to identify the factors/interactions, (2) to identify the levels of each factor, (3) to select an appropriate orthogonal array (OA), (4) to assign the factors/interactions to columns of the OA, (5) to conduct the experiments, (6) to analyse the data and determine the optimal levels, and (7) to conduct the confirmation experiment.

## 3 DESIGN OF SOIL-NAILED EXCAVATION

In this study, the hardening small strain (HSS) model is applied which is an extension of hardening-soil (HS) model in PLAXIS V8.5. Benz (2007) gave a detailed description of this model and indicated that the main difference between HSS and HS is the additional failure criterion and a refined flow rule. To describe the behaviour of soil at small strain which is less than  $10^{-3}\%$ , two additional parameters, the initial shear modulus  $G_0$  and the shear strain  $\gamma_{0.7}$ , are defined in HSS. The parameter  $\gamma_{0.7}$  is the strain where the secant shear modulus is reduced to 70% of  $G_0$ . The shear strain  $\gamma_{0.7}$  can be obtained from the plasticity index (PI) of soil and the initial shear modulus  $G_0$  can be derived from the relationship with initial stiffness  $E_0$ .

In this study, the parameters considered as the most effective in design of soil-nailed excavations are bar size (length and diameter), horizontal spacing of bars, shotcrete thickness and drill hole diameter. Mechanical parameters of assumed soils are given in Table 1. Analyses were accomplished for two different soil types of clay and sand, each with two different excavation depths.

Table 1: Mechanical parameters of soils

Soil type	$\gamma$ (kN/m <sup>3</sup> )	C <sup>a</sup> (kPa)	b	c	$E_{50}^{ref\ d}$ (MPa)	$E_{oed}^{ref\ e}$ (MPa)		$G_0^{ref}$ (MPa)	Bond strength (kPa)
CL	17	50	10	0	25	75	0.0002	100	60
SM	19	10	32	5	50	150	0.0002	150	150

<sup>a</sup> C is cohesion, <sup>b</sup> is friction angle, <sup>c</sup> is dilatancy angle, <sup>d</sup>  $E_{50}^{ref}$  is secant stiffness in CD triaxial test, <sup>e</sup>  $E_{oed}^{ref}$  is tangent oedometer stiffness.

### 3.1 Excavation in clayey soil

At first, Taguchi method is applied to clayey soil for excavation depths of 15 and 20 meters. The variables and their levels are shown in table 2.

Table 2: Variables and their levels for each depth of excavation in clayey soil

Excavation depth (m)	15				20			
	1 <sup>st</sup> level	2 <sup>nd</sup> level	3 <sup>rd</sup> level	4 <sup>th</sup> level	1 <sup>st</sup> level	2 <sup>nd</sup> level	3 <sup>rd</sup> level	4 <sup>th</sup> level
Horizontal space (m)	1	1.25	1.5	1.75	1	1.25	1.5	1.75
Shotcrete thickness (cm)	10	12	15	20	10	12	15	20
Drillhole diameter (mm)	110	115	120	130	110	115	120	130
Maximum bar length (m)	9	12	14	16	10	12	14	16
Bar diameter (mm)	32	40			32	40		

According to factors shown in table 2, there are 4 variables with 4 levels and 1 variable with 2 levels. Accordingly, the L16 orthogonal array of Taguchi method was selected. Different combinations of these factors will make different conditions for analyses as shown in table 3. 16 analyses were carried out using the finite elements code; PLAXIS V8.5. In each analysis, external and internal stability obligations based on FHWA code were satisfied. Note that to have identical finite elements mesh for each excavation depth, the vertical spacing of nails is considered to be constant.

In this research, the selected objective function in Taguchi method is total cost, thus to have an economical design, the quality criterion is “smaller is better”. Total cost includes material and operational expenses. As shown in table 4, material costs involve bar, bearing plate, grout and welded wire mesh costs while operational costs contain drilling, placing, grouting and shotcrete costs. As an example of analyses, the total computed expenses for a 15-meter excavation in clayey soil is given in table 5.

Then, Taguchi analysis was carried out according to selected objective function. This method can yield the best level of each factor to have the most economical design.

After Taguchi analysis, the optimum design for two excavation depths of 15 and 20 meters was obtained.

*Table 3: L16 orthogonal array for analysis in a 15- meter excavation depth in clayey soil*

Analysis number	Factors				
	Horizontal space	Shotcrete thickness	Drillhole diameter	Minimum bar length	Bar diameter
1	1	1	1	1	1
2	1	2	2	2	1
3	1	3	3	3	2
4	1	4	4	4	2
5	2	1	2	3	2
6	2	2	1	4	2
7	2	3	4	1	1
8	2	4	3	2	1
9	3	1	3	4	1
10	3	2	4	3	1
11	3	3	1	2	2
12	3	4	2	1	2
13	4	1	4	2	2
14	4	2	3	1	2
15	4	3	2	4	1
16	4	4	1	3	1

*Table 4: Material and Operational costs*

Material costs						Operational costs							
per unit length			per unit area			per unit length			per unit area				
nail	bearing plate	grout	welded wire mesh	shotcrete	waler bar	drilling	placing	grouting	welded wire mesh and shotcrete				
0.7 \$/Kg	0.8 \$/Kg	4.5 \$/m <sup>3</sup>	0.8 \$/Kg	4.5 \$/m <sup>3</sup>	0.7 \$/Kg	16 \$/m			10 cm	12cm	15cm	20cm	
									5 \$/m <sup>2</sup>	6 \$/m <sup>2</sup>	7 \$/m <sup>2</sup>	9.4 \$/m <sup>2</sup>	

**Table 5: Properties and total cost of each analysis in a 15-meter excavation in clayey soil**

Analysis number	Horizontal space (m)	Shotcrete thickness (cm)	Drillhole diameter (mm)	Maximum bar length(m)	Bar diameter (mm)	FS <sub>G</sub> <sup>a</sup>	FS <sub>P</sub> <sup>b</sup>	FS <sub>T</sub> <sup>c</sup>	Bar density (m/m <sup>2</sup> )	Material cost (\$/m <sup>2</sup> )	Operational cost (\$/m <sup>2</sup> )	Total cost (\$/m <sup>2</sup> )
1	1	10	110	9	32	1.867	1.99	2.57	8.00	49.8	130.0	179.8
2	1	12	115	12	32	1.886	2.06	2.55	10.00	59.3	162.5	221.8
3	1	15	120	14	40	1.911	1.94	3.59	10.67	88.6	173.6	262.2
4	1	20	130	16	40	1.970	2.35	4.02	11.07	98.2	182.3	280.6
5	1.25	10	115	14	40	1.922	2.17	3.59	8.53	72.0	138.3	210.3
6	1.25	12	110	16	40	1.971	2.12	3.67	8.85	74.4	144.5	218.9
7	1.25	15	130	9	32	1.861	1.96	2.14	7.84	48.3	129.4	177.7
8	1.25	20	120	12	32	1.878	1.98	2.35	8.00	55.6	134.4	190.0
9	1.5	10	120	16	32	1.976	2.18	2.22	7.78	47.0	126.6	173.6
10	1.5	12	130	14	32	1.923	2.14	2.01	7.51	45.9	123.6	169.5
11	1.5	15	110	12	40	1.881	2.07	3.14	7.73	65.8	127.7	193.4
12	1.5	20	115	9	40	1.851	2.35	3.44	7.73	72.5	130.2	202.6
13	1.75	10	130	12	40	1.872	2.52	3.24	7.66	64.7	124.7	189.4
14	1.75	12	120	9	40	1.893	2.56	2.99	7.54	63.8	124.1	187.9
15	1.75	15	115	16	32	1.985	2.33	1.85	7.51	45.4	124.2	169.6
16	1.75	20	110	14	32	1.922	2.50	2.08	7.47	51.8	126.1	177.9

<sup>a</sup> FS<sub>G</sub> is the global stability safety factor which should be more than 1.35 according to FHWA

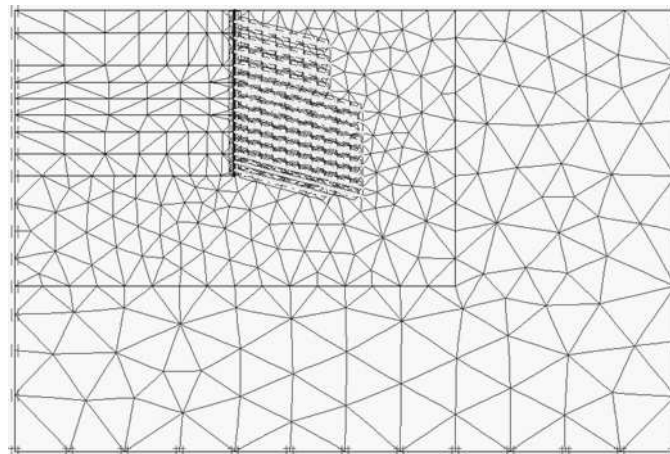
<sup>b</sup> FS<sub>P</sub> is the nail pull-out safety factor which should be more than 2 according to FHWA

<sup>c</sup> FS<sub>T</sub> is the nail tensile safety factor which should be more than 1.5 according to FHWA

**Table 6: Properties and total cost of the optimum design for each depth of excavation in clayey soil**

		Horizontal space (m)	Shotcrete thickness (cm)	Drillhole diameter (mm)	Minimum bar length(m)	Bar diameter (mm)	FS <sub>G</sub>	FS <sub>P</sub>	FS <sub>T</sub>	Bar density (m/m <sup>2</sup> )	Total cost (\$/m <sup>2</sup> )
Excavation depth(m)	15	1.75	10	110	9	32	1.883	2.00	1.93	5.2	128
	20	1.75	12	130	12	32	1.516	2.07	1.51	7.45	187

The generated finite elements mesh for optimum design in a 15-meter excavation is presented in figure 1. Note that in clayey soil, the bar length is increased with depth. This is because of very low bond strength of clayey soils. So to avoid pull out failure we need longer bars in lower levels. As shown in figure 1.



**Figure 1. Finite elements mesh of optimum design in a 15-meter excavation in clayey soil**

### 3.2 Excavation in sandy soil

A similar procedure was carried out for excavations in sandy soil. Calculating the objective function is same as for clayey soil. With application of Taguchi method, the optimum design for this type of soil was achieved. Properties and also total cost of the optimum design for each depth of excavation are shown in table 7.

Table 7: Properties and total cost of the optimum design for each depth of excavation in sandy soil

		Horizontal space (m)	Shotcrete thickness (cm)	Drillhole diameter (mm)	Minimum bar length(m)	Bar diameter (mm)	FS <sub>G</sub>	FS <sub>P</sub>	FS <sub>T</sub>	Bar density (m/m <sup>2</sup> )	Total cost (\$/m <sup>2</sup> )
Excavation depth(m)	15	1.75	10	91	9	32	1.590	2.15	1.90	3.66	96
	20	1.75	10	110	10	40	1.350	2.00	1.56	4.97	122

The generated finite elements mesh for optimum design in a 15-meter excavation is presented in figure 2. In sandy soils, bar lengths is decreased with depth.

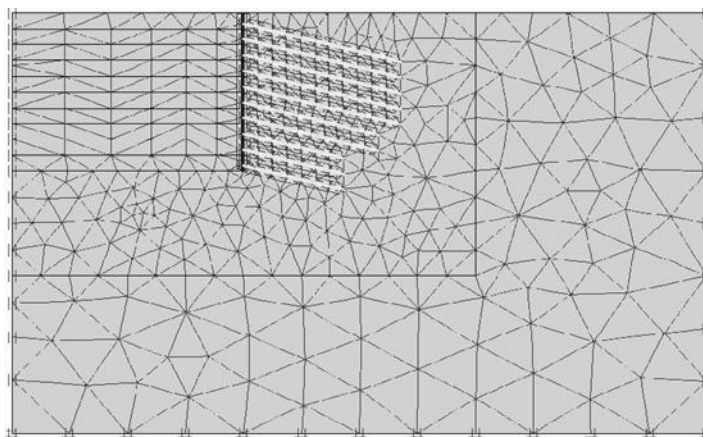


Figure 2. Finite elements mesh of optimum design in a 15-meter excavation in sandy soil

#### 4 CONCLUSION

In this paper, design optimization of soil nailed excavations was accomplished by Taguchi method. Two different soils of clay and sand were considered both for two vertical excavations of 15 and 20 m. In each case, an optimum design of nails and shotcrete is obtained with satisfied safety factors and allowable displacements. The approach revealed that the optimum design can be successfully achieved by a limited number of analyses through a systematic manner.

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