Optimization of Rock Bolt and Concrete Lining Combination: A Case of AKH Railway Tunnel Project

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Abstract. Concrete lining and rock bolts are usually provided to support excavated tunnels on different ground conditions. These two support systems are worthy and need in-depth consideration as their impact on tunnel cost and deformation are critical. The optimum use of these support systems is a challenge that demands the best design solution. In order to facilitate the determination of the optimal combination of the two, an optimization scheme has been devised in this study using Finite Element Analysis (FEA) and MATLAB software for a specific under-construction tunnel in Karakore, Ethiopia. The tunnel displacements found from the FEA and the cost of tunnel construction were modeled using polynomial functions with a multi-objective optimization since the problem has two objectives. Considering displacement and cost functions, the optimum combination of rock bolt and concrete lining has been found. The result shows that the optimum combination can be found by increasing the number of rock bolts. The finite element analysis gives a total displacement of 6.34 cm in the best scenario case, which is slightly greater than the observed total displacement of about 6 cm. The total cost of rock bolt and concrete lining for the optimum combination becomes $30,700 per meter length of tunnel rock bolt and concrete lining construction.

Keywords: Rock bolt · Concrete lining · Optimization · Finite element method · MATLAB

1 Introduction

Based on the ground condition, rock bolts and concrete lining are provided as means of support for tunnels. These two support systems have an impact on the cost and the convergence of the tunnel. Designing the rock bolt for underground excavation considers the type of bolt (Smith 1993), bolt pattern, spacing, and size (Nguyena et al. 2015). In addition, bolt profile configuration affects load transfer capacity between the bolt and grout (Mostafa et al. 2015). The optimal profile geometry of the rock bolt is affected by the mechanical properties of the grout and the confining pressure (Cao et al. 2014). The bolt-grouting combined support system is proposed to prevent high stress (Chen et al.

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2016). By considering the different properties of rock bolt, the designer has to carry out an optimum rock bolt design.

The cause and effect of parameters are collected by using the fishbone diagram (Meyer et al. 2013). The fishbone diagram identifies many possible causes for an effect or problem. A Pareto chart is a type of chart that representing individual values in descending order by bars, and the cumulative total by the line. The purpose of the Pareto chart is to highlight the most influential factors (Visual-paradigm 2018).

The process of designing tunnel support lining involves the determination of design variables based on experience and intuition. The development of some standard methods for producing optimal designs would have practical significance. The subject of optimization of tunnel lining (Pérez-Romero et al. 2006) has been treated such as in topology optimization (Liu and Jin 2006; Yin and Yang 2000; Nguyen et al. 2014), shape optimization (Ghabraie et al. 2010), multi-objective optimization (Tonon et al. 2002) and modified colliding bodies optimization (Fazli 2017). Gamultiobj is one of multi-objective solver which is used to solve problems in several variables (Messac 2015). The optimum combination of rock bolt and concrete lining is found based on the principles of optimization that the objective function is optimized while performance and other constraints are satisfied (Arora 2004; Papalambros and Wilde 2000; Ravindran 2006).

The design of tunnels cannot proceed simply in the same way as a structure being exposed to well-defined loading conditions. In addition, there is no universally accepted tunnel design method; rather experience and engineering judgment play a great role. Besides the engineering judgment, the support system could be designed prudently to get an optimum solution so as to control the convergence of the tunnel (Kersten 2008).

Ethiopia has implemented many tunneling projects after launching the railway network throughout its corridors. Since there is little experience in the design and construction of tunnels in the country, this study aims at proposing an optimization method of tunnel support design which can be a contribution to the practical applications by considering the different configurations of rock bolt and concrete linings. This has been done by using numerical methods by employing the ground data taken from the Awash Kombolcha Haragebeya (AKH) railway tunnel project. Since there is a lack of refined parameters for seismic analyses, like site-specific ground motion data, the analysis considered only static conditions.

2 Design of Data for Optimization

Once the possible collections of parameters are determined through the fish-bone diagram (Meyer et al. 2013), the Pareto chart is developed. Pareto chart is used in the selection of those very influential parameters and narrows down the parameters to use in the design of the experiment (Visual-paradigm 2018). The number of rock bolt and concrete lining thickness have been selected as causal parameters. The effect of small change in parameter magnitude is first determined by using Eq. 1, while the cumulative result of parameters, known as the response, is found using Eq. 2. The parameters with higher coefficients are indicated to have more effect on the cost and settlement of the tunnel. Once the parameters are determined, the next step is the design of data for optimization.

$$a_i p_i = a_i p_{oi} + a_i \Delta p_i \tag{1}$$

where, a_i = regression coefficients
p_{0i} = operating mean parameter magnitude and
Δp_i = small change in parameter magnitude.

$$Response = \sum_{i=1}^{n} a_i p_i \tag{2}$$

where, a_i = regression coefficients and
p_i = parameters (number of rock bolt and thickness of concrete lining).

The design of data for optimization involves the generation of the combination of parameters in which the study becomes easy to understand in a better way. For this particular research, two levels of design of data are used as shown in Table 1. The number of rock bolt is labeled as B and concrete lining thickness as L. The two parameters, B and L vary between 7 and 19 and 10 cm and 40 cm respectively, are taken based on practical considerations.

Table 1. Parameter combinations used in the analysis

S. no	Combination code	Number of rock bolt	Lining thickness (cm)
1	B_1L_1	7	10
2	B_1L_2	7	20
3	B_1L_3	7	25
4	B_1L_4	7	30
5	B_1L_5	7	40
6	B_2L_1	11	10
7	B_2L_2	11	20
8	B_2L_3	11	25
9	B_2L_4	11	30
10	B_2L_5	11	40
11	B_3L_1	15	10
12	B_3L_2	15	20
13	B_3L_3	15	25
14	B_3L_4	15	30
15	B_3L_5	15	40

(*continued*)

Table 1. (*continued*)

S. no	Combination code	Number of rock bolt	Lining thickness (cm)
16	B_4L_1	19	10
17	B_4L_2	19	20
18	B_4L_3	19	25
19	B_4L_4	19	30
20	B_4L_5	19	40

To achieve the objective of the research, the flowchart as shown in Fig. 1 was developed to show the algorism followed from the design of data optimization up to the numerical analysis for optimized design combination.

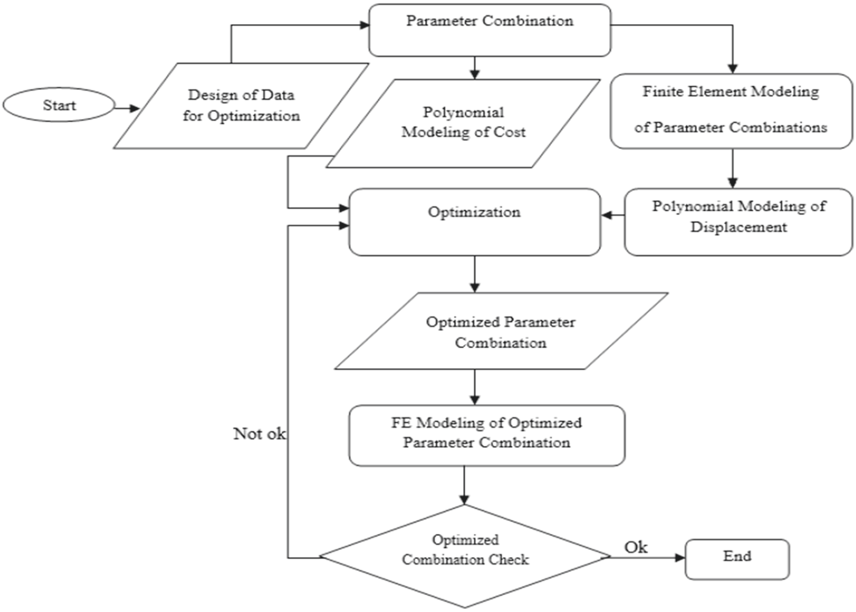

Fig. 1. Flowchart for conducting optimization

3 Parameter Optimization Process

After preparing the design data combinations, the numerical analysis was performed for each combination. The numerical analysis was done for a typical ground condition at 178 + 300 m chainage of the tunnel (T04) shown in Fig. 2. The ground has a Rock Mass Rating (RMR) value of 21–40 according to the engineering classification of rocks (Bieniawski 1989).

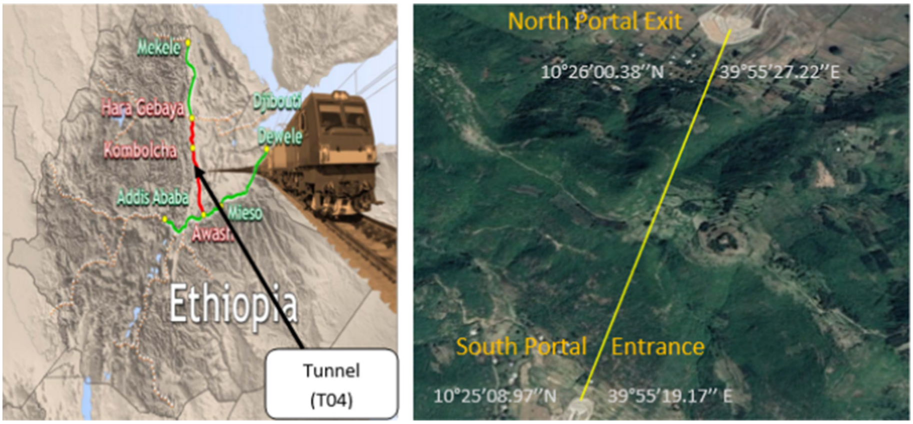

Fig. 2. Geographical location of tunnel T04

The ground condition and support systems data shown in Table 2 are taken as inputs for the numerical analysis. From a numerical computation using Plaxis 2D, the displacement of the tunnel has been determined for each combination.

Table 2. Ground condition and support system data

A. Ground condition

Rock type	Excavation type	Overburden (m)	Unit weight, γ (kN/m^3)	Cohesion, C (kPa)	Friction angle, φ	Modulus of elasticity, E (MPa)	Poisson ratio, v
A	Full excavation	50	24	400	37	250	0.25
B-C	Full excavation	30	22	100	36	160	0.28

B. Rock bolt characteristics

Length (m)	Bar diameter (mm)	Longitudinalspacing (m)	Ultimatecapacity (kN)	Axial stiffness, EA (kN/m)
4	26	1	230	$7.08 * 10^4$

C. Lining characteristics

Support Type	Shotcrete	Lining
Thickness (m)	0.2	0.3
Modulus of elasticity, Ec (GPa)	15	31
Poisson's coefficient, ν	0.2	0.2
Axial stiffness (MN/m)	3000	9300
Flexural stiffness (MNm^2/m)	10	69.75
Self-weight (kN/m/m)	5	7.5

The perimeter of the concrete lining was 34 m and the analysis was performed by considering plane strain conditions. The unit cost of rock bolt and concrete lining was $290 and $3100 respectively. The unit cost is adopted from the contractor for the year 2017 and is assumed to vary proportionally with time. Rock bolt cost includes all costs including installation (material, grout, equipment), whereas the concrete lining cost includes all costs up to casting (concrete material, formwork, and equipment). The calculated displacement of the tunnel from the numerical analysis together with the associated cost of the tunnel is shown in Table 3, for the chosen cases.

Table 3. Displacement and cost of tunnel

S. no	Combination code	Number of rock bolt	Concrete lining thickness (cm)	Total displacement (mm)	Total cost of rock bolt and concrete lining ($)
1	B_1L_1	7	10	65.14	12,570
2	B_1L_2	7	20	64.62	23,110
3	B_1L_3	7	25	64.4	28,380
4	B_1L_4	7	30	64.21	33,650
5	B_1L_5	7	40	63.96	44,190
6	B_2L_1	11	10	64.75	13,730
7	B_2L_2	11	20	64.23	24,270
8	B_2L_3	11	25	64.01	29,540
9	B_2L_4	11	30	63.82	34,810
10	B_2L_5	11	40	63.57	45,350
11	B_3L_1	15	10	64.13	14,890
12	B_3L_2	15	20	63.61	25,430
13	B_3L_3	15	25	63.4	30,700
14	B_3L_4	15	30	63.2	35,970
15	B_3L_5	15	40	62.95	46,510
16	B_4L_1	19	10	63.34	16,050
17	B_4L_2	19	20	62.82	26,590
18	B_4L_3	19	25	62.63	31,860
19	B_4L_4	19	30	62.41	37,130
20	B_4L_5	19	40	62.16	47,670

The numerical analysis results have been used in order to formulate a polynomial model for each parameter combination. The numerical results in column 5 are best fitted and correlated using a second-order polynomial surface model as shown in Eq. 3. The data from Column 3, 4 and 5 of Table 3 are used to derive the tunnel displacement function Q(x,y), whose graphical representation is shown in Fig. 3.

$$Q(x, y) = 66.09 + 0.000135x - 0.07211y - 0.005763x^2 - 1.239 * 10^{-9}xy + 0.0006522y^2 \quad (3)$$

where, x = number of rock bolt and
y = lining thickness in cm.

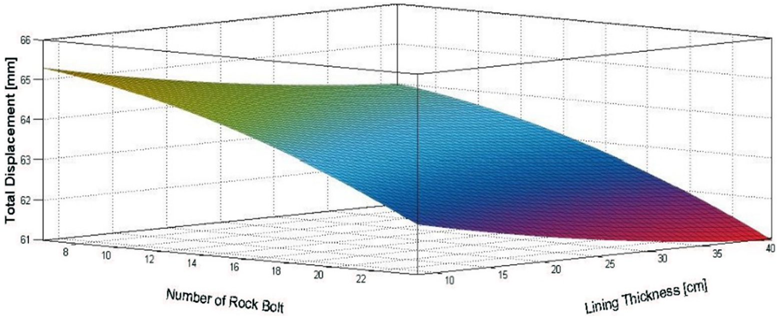

Fig. 3. Graphical presentation of tunnel settlement from numerical result

Similarly, the cost results are represented using the second-order polynomial model as shown in Eq. 4. The data from columns 3, 4 and 6 are used to derive the cost function F(x,y), whose graphical presentation is shown in Fig. 4.

$$F(x, y) = 290x + 1054y - 1.567 * 10^{-12}x^2 + 4.729 * 10^{-13}xy - 2.873 * 10^{-12}y^2 \quad (4)$$

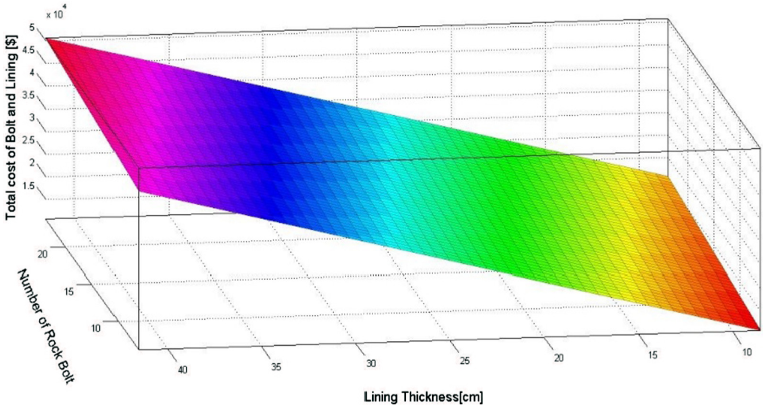

Fig. 4. Cost function graphical representation

where, x = number of rock bolt and
y = lining thickness in cm.

The two parameter correlation functions of Eq. 3 and 4 are used for optimization. The dimensionless relationship between the cost and displacement of the tunnel is shown in Fig. 5. While the cost of the tunnel is directly proportional to parameter increment, the displacement of the tunnel is inversely proportional to parameter increment.

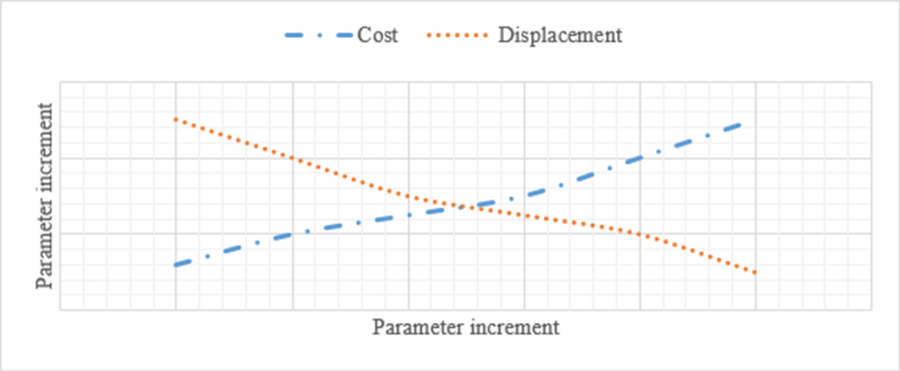

Fig. 5. Dimensionless relationship between cost and displacement

The Pareto front graph is derived from the two objective functions and plotted in Fig. 6, showing the relationship between the cost and displacement objective functions.

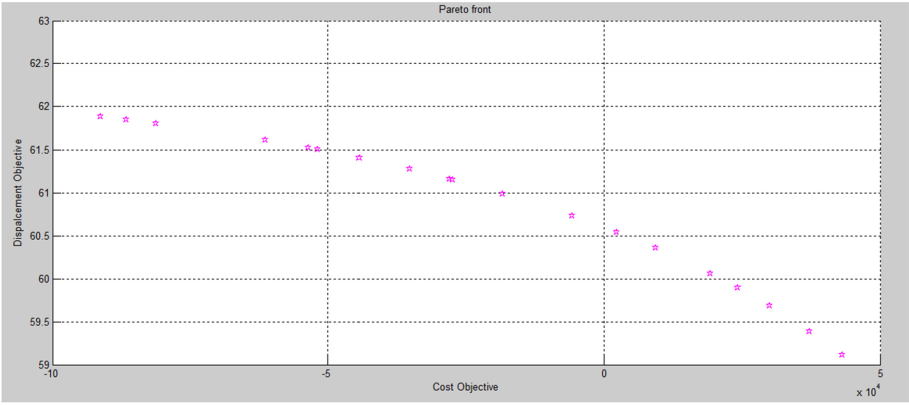

Fig. 6. Pareto front displacement and cost relationship

In the Pareto front, there is no single solution and for a nontrivial multi-objective optimization problem, no single solution occurs that simultaneously optimizes each objective (Emmerich and Deutz 2018). In that case, there exists a possibility of an infinite number of Pareto optimal solutions. Since the problem has two objective functions, multi-objective optimization is employed.

Considering the cost and displacement functions separately, the optimal result using MATLAB Gamulti Objective Solver obtained are 7 bolts with 10 cm thick lining and 19 bolts with 40 cm thick lining respectively. But these values are at the boundary of the constraints. Case scenario 1 (7 bolts with 10 cm lining) gives more settlement than the 20th case scenario, but it is cost-effective. On the other hand, case scenario 20, which shows less settlement than the other case scenarios is too costly. Therefore, considering the two extremities (case 1 and case 20), the optimum combination could be a combination that meets the two objective functions.

Even if the problem is constrained, the critical parameters are determined and tested for local maximum or minimum for the function Q(x,y) and F(x,y) using Boussinesq Eq. 5.

$$D = \left(\frac{\partial^2 Q}{\partial^2 x}\right)\left(\frac{\partial^2 Q}{\partial^2 y}\right) - \left(\frac{\partial^2 Q}{\partial X\,\partial Y}\right)^2 \tag{5}$$

For the displacement function, the critical parameters are determined by setting $\left(\frac{\partial \mathrm{Q}}{\partial \mathrm{x}}\right) = 0$ and $\left(\frac{\partial \mathrm{Q}}{\partial \mathrm{y}}\right) = 0$. Similarly, for the cost function, the critical parameters are determined by setting $\left(\frac{\partial \mathrm{F}}{\partial \mathrm{x}}\right) = 0$ and $\left(\frac{\partial \mathrm{F}}{\partial \mathrm{y}}\right) = 0$. The critical points are found by solving the two simultaneous equations. The critical points found for the two functions do not lead to the optimum solution. The optimal combination of rock bolt and concrete lining with the constraints given is case scenario 13, which has 15 bolts and 25 cm thick lining, which can be considered as the optimum solution for this condition.

The variation of the number of rock bolt and lining thickness on the effect of cost of the tunnel shows a significant change. Increasing the number of rock bolt would likely decrease the convergence and cost of the tunnel provided that the spacing of rock bolt is not less than the minimum spacing provided on the Tunnel Design Manual (Jeremy et al. 2009). The minimum concrete thickness with rock bolts can be used for the rocky ground conditions. Therefore for the rocky ground conditions, the optimum combination can be found by starting from providing minimum rock bolts with minimum lining thickness as long as the other design factors are satisfied by the combination.

4 Comparison Between the Results of Contractor Design and the Optimum Combination

With the aim of assessing the effectiveness of the optimization, a comparison of the contractor's provisions has been made with the findings of this research. Since the contractor followed similar approaches using Plaxis 2D as in the current study, the displacements achieved by employing 11 rock bolts and 30 cm lining were close to one another. The optimization level of the selected support system as compared to the provisions of the contractor is compiled in Table 4.

The two design combinations show a variation in terms of number of rock bolt and thickness of concrete lining. The contractor design combination has less number of rock bolts than the optimized design combination, but thicker concrete lining than the optimized design combination. Because the rock bolts can reduce the convergence of

Table 4. Results of optimized and contractor design combination

Design combination	Contractor (actual)	Optimized	Comment
Parameter combination	11 rock bolts 30 cm lining	15 rock bolts 25 cm lining	The observed total displacement after Support installations was 1.5 cm. The tunnel displacement before the installation of instrument is unknown. But this value usually is 3 to 4 times of the current observed instrument reading which becomes nearly 6 cm
Displacement	6.38 cm	6.34 cm	
Cost per meter (Longitudinal)($)	34840	30700	
Type of analysis and analysis software	FEA, Plaxis 2D	FEA, Plaxis 2D	

the tunnel, the tunnel at an optimized design combination deforms less than the tunnel at the contractor design combination. The total displacement around the tunnel at optimum design combination is shown in Fig. 7. Since the observed displacement is lower than the predicted displacement from the numerical analysis, the optimized combination can be considered as effective.

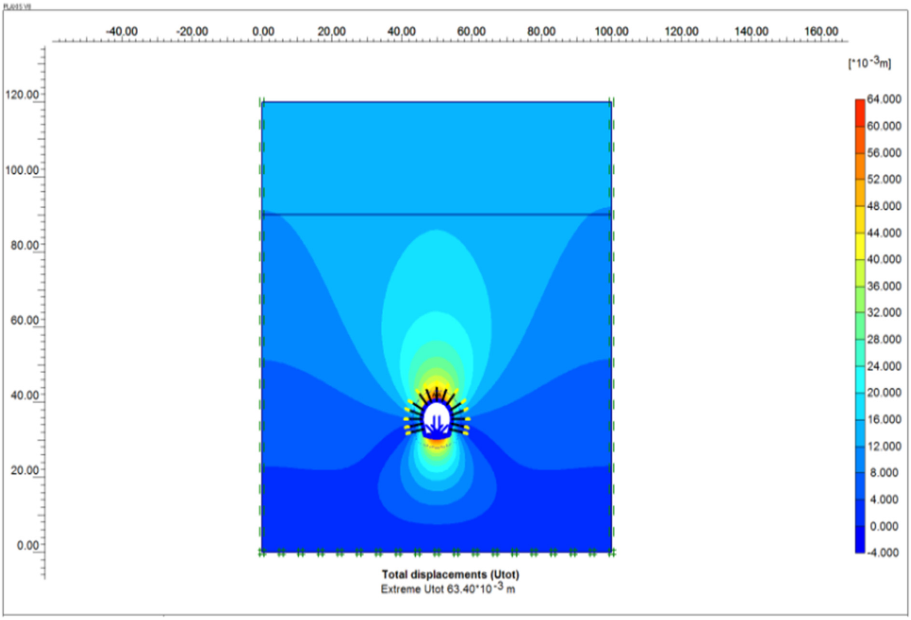

Fig. 7. Total displacement of the optimized combination

The design provided by the contractor is more expensive than the design combination optimized in this research. When the two design combinations are compared per meter of rock bolt and concrete lining construction, a difference of $4140 is observed.

5 Conclusion

In this research, optimization of rock bolt and tunnel lining combination has been performed by employing the numerical tools Plaxis 2D and MATLAB. The possibility of optimization of tunnel support has been assessed by taking a specific tunnel section from the Awash - Kombolcha - Haragebeya project, by modeling the cost of the tunnel using a polynomial function. The tunnel displacements found using the FEA were also modeled by using a polynomial function. The optimization potential has been illustrated by considering the displacement and cost functions per meter of tunnel length. The optimum combination was found at increased number of rock bolt and reduced lining thickness. The tunnel at the optimum design combination deforms less than the actual design. The optimized design gives a reduction in $4140 per meter length of the tunnel as compared to the provisions of the contractor.

Declaration of Interest. The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article.

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