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Effect of Objective Function on the Optimization of Highway Vertical Alignment by Means of Metaheuristic Algorithms

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ABSTRACT: The main purpose of this work is the comparison of several objective functions for optimization of the vertical alignment. To this end, after formulation of optimum vertical alignment problem based on different constraints, the objective function was considered as four forms including: 1) the sum of the absolute value of variance between the vertical alignment and the existing ground; 2) the sum of the absolute value of variance between the vertical alignment and the existing ground based on the diverse weights for cuts and fills; 3) the sum of cut and fill volumes; and 4) the earthwork cost and then the value of objective function was compared for the first three cases with the last one, which was the most accurate ones. In order to optimize the raised problem, Genetic Algorithm (GA) and Group Search Optimization (GSO) were implemented and performance of these two optimization algorithms were also compared. This research proves that the minimization of sum of the absolute value of variance between the vertical alignment and the existing ground, which is commonly used for design of vertical alignment, can't at all grantee the optimum vertical alignment in terms of earthwork cost.

Keywords: Earthwork Volumes, Group Search Optimization (GSO), Objective Function, Optimization, Optimum Vertical Alignment.

INTRODUCTION

There are three key stages for designing highways including designing the horizontal alignment, designing vertical alignment, and calculating the earthwork volumes. In fact, in the initial stage, the location or horizontal alignment of the highway is designed based on the topographic maps and the maximum allowable grade, and in the second stage the vertical alignment or project should be designed according to the design criteria and minimizing construction costs. In the third step, considering the typical cross section, the cross sections along the highway were printed and the fill and cut volumes are estimated.

After designing the horizontal alignment, the most effective parameter on the highway construction costs is the optimum design of the vertical alignment for decreasing the

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earthwork volumes. Moreover, the correct design of the vertical alignment is very effective on the safety and cost of the vehicles. Some works emphasized that the vertical alignment should be designed as close as possible to the existing ground line (Garber and Hoel, 2014; Abbey, 1992; AUSTROADS, 1993; Papacostas and Prevedouros, 1993; Banks, 2002). In contrast, some references highlight other factors like earthwork minimization and achieving cut-fill balance, to design the vertical alignment (AASHTO, 2011; CALTRANS, 1995).

Enhancing the vertical alignment minimizes the total value of the earthwork costs. To decrease the highway construction costs, a systematic approach should be implemented to choose the optimal vertical alignment. Besides minimizing earthwork costs, some restrictions like the maximum and minimum grade of tangents, minimum length of vertical curves, minimum height of bridges, and non-overlapping of vertical curves should be evaluated to design the vertical alignment.

Until now, numerous researches have attempted to optimize the vertical alignment for highway and railway routes. In Table 1, some of these researches and their main characteristics have been represented.

As shown, since calculation of earthwork volume is complicated, in the majority of previous researches, the sum of the absolute value of variance between the vertical alignment and the existing ground has been considered as objective function to tackle the problem of optimum vertical alignment. Moreover, in some other researches which have considered the earthwork volume as the objective function, this volume has been obtained by using approximate approaches and hence, the exact volume of the earthwork has not been considered in most of previous works. So, one of the main purpose of the present research is optimizing vertical alignment based on the accurate estimation of earthwork volumes.

In this work, the comparison of different objective functions for optimization of vertical alignment is investigated. The objective function is considered as four forms including: 1) the sum of the absolute value of variance between the vertical alignment and the existing ground; 2) the sum of the absolute value of variance between the vertical alignment and the existing ground based on the diverse weights for cuts and fills; 3) the sum of cut and fill volumes; and 4) the earthwork cost.

The main purpose of vertical alignment design is decreasing the earthwork cost; therefore, the fourth objective function is the most appropriate one (Fwa et al., 2002; CALTRANS, 1995; AASHTO, 2011). Although minimizing the earthwork cost is the most appropriate objective function for designing the vertical alignment, but due to the complexity, minimizing the difference between the vertical alignment and the ground line at the road centerline is usually used for the manual design of the vertical alignment.

On the other hand, run time for estimation of earthwork cost is much higher than estimation of difference between the vertical alignment and ground line at the road centerline, which makes it almost impossible to use this function for routine design of vertical alignment. So in this research, to evaluate other objective functions, the optimum vertical alignment is achieved first by other three objective functions and then, their results will be compared with that of the optimum vertical alignment according to the earthwork cost. Besides, a comparison was conducted between the performance of two different optimization algorithms including Genetic Algorithm (GA) and Group Search Optimization (GSO) in terms of the problem of vertical alignment optimization.

Table 1. A summary of researches conducted on optimizing the vertical alignment

Reference	Objective function	Constraint	Method
(Easa, 1988)	Minimization of earthmoving	The slop of the tangent	Linear programming
(Easa, 1999)	The sum of the absolute deviations between the observed profile and the vertical curve	-	Linear programming
(Dabbour et al., 2002)	The sum of difference between vertical alignment and existing ground profile	Maximum allowable grade, maximum vertical curvature and non-overlapping of vertical curves	Nonlinear programming
(Göktepe et al., 2008)	Using Fuzzy system to determine swell and shrinkage factor	-	Fuzzy method
(Göktepe et al., 2009)	The sum of squared differences between calculated weighted ground elevations and grade elevations	Maximum allowable gradient and sight distance	Fuzzy method and genetic algorithm
(Göktepe et al., 2010)	The sum of differences between calculated weighted ground elevations and grade elevations	Maximum allowable gradient and sight distance	Dynamic programming
(Wang et al., 2011)	The sum of difference between vertical alignment and ground profile in the center line of the road	Maximum allowable gradient, vertical curvature constraint and sight distance	Genetic algorithm
(Bababeik and Monajjem, 2012)	Total construction and operating costs	Maximum allowable grade	Direct search method and genetic algorithm
(Rahman, 2012)	Total excavation, embankment, and hauling cost	Natural blocks and side slopes	Mixed integer linear programming
(Mil and Piantanakulchai, 2013)	The sum of difference between vertical alignment and ground profile in the center line	Maximum allowable gradient and minimum vertical curve length	Polynomial regression model
(Li et al., 2013)	Total earth work, land acquisition, bridges, tunnels, retaining structure and length-related costs	Maximum allowable gradient, vertical curvature and minimum curvature radius	Dynamic Programming
(Kazemi and Shafahi, 2013)	The sum of construction costs and earthwork costs	Maximum grade and minimum length of vertical curves	Parallel processing and PSO algorithm
(Shafahi and Bagherian, 2013)	Total right-of-way and earthwork costs	Minimum radius, maximum and minimum length for vertical curves	PSO algorithm
(Tunahoglu and Soycan, 2014)	The sum of difference between vertical alignment and ground profile in the center line of the road	Maximum and minimum allowable grades	Searching algorithm
(Hare et al., 2014)	Minimization of earthmoving	Side slopes and physical blocks in the terrain	mixed-integer linear programming and quasi-network flow
(Al-Sobky, 2014)	The earthwork balance and equal cut and fill quantities	Minimum grade of tangents, minimum length of vertical curves	Linear programming
(Hare et al., 2015)	The minimization of the total excavation cost, embankment cost and hauling cost.	Side-slopes of the road and the natural blocks	mixed-integer linear programming
(Beiranvand et al. 2017)	The minimization of the total excavation cost and embankment cost	The borrow and waste pit and the natural blocks	Multi-haul quasi network flow model
(Ghanizadeh and heidarabadizadeh, 2018)	minimization of Earthwork cost	Maximum and minimum grade of tangents, minimum length of vertical curves, compulsory points	colliding bodies optimization algorithm

OPTIMIZATION ALGORITHMS

Genetic Algorithm

So far, various metaheuristic optimization algorithms have been developed and employed successfully in the field of civil infrastructure engineering (Shafahi and Bagherian, 2013; Moosavian and Jaefarzade, 2015; Hadiwardoyo et al., 2017; Ghanizadeh and Heydarabadizadeh, 2018; Husseinzadeh Kashan et al., 2018). Genetic algorithm (GA) is one of the first and most important of these algorithms. Holland (1975) presented GA with the inspiration of Darwin's theory about the survival of fittest. One of the capabilities of stochastic algorithms is to work over a set of solutions called population. Each member of the population is called a chromosome $\vec{X}_i = [x_1, x_2, \dots, x_D]$ where D: is the number of gens. The standard version of the GA is organized by three operators including reproduction, crossover, and mutation. After applying these operators, the new population would be created. This process is iterated until the stopping criterion is met, and the chromosome with the best fitness would be introduced as the optimal solution. The details of the reproduction, crossover, and mutation operators are described in the following.

- Reproduction: In a simple way, two members of the population are selected randomly then the member with less fitness is removed from the population and the one with more fitness is put in place. This operator is done for ($P_r \times N$) members of the population. Where, P_r and N are the probability of the reproduction and the size of the population, respectively.
- Crossover: A crossover operator selects two members of the population randomly. Then, it creates two new chromosomes and puts them at the place of the old chromosomes. The crossover operator is usually applied to a number of pairs determined as $(P_{tc} \times N)/2$, where P_{tc} and N: are the probability of the crossover and the population size, respectively. Let $\vec{X}_i(t)$ and $\vec{X}_j(t)$ be two randomly selected chromosomes and $\vec{X}_i(t)$ has the smaller fitness value than $\vec{X}_j(t)$, then the crossover relations are as follows.

$$\begin{aligned}\vec{X}_i(t+1) &= \vec{X}_i(t) + \vec{\gamma}_1 (\vec{X}_i(t) - \vec{X}_j(t)) \\ \vec{X}_j(t+1) &= \vec{X}_j(t) + \vec{\gamma}_2 (\vec{X}_i(t) - \vec{X}_j(t))\end{aligned} \qquad (1)$$

where $\vec{\gamma}_1$ and $\vec{\gamma}_2 \in [0,1]^D$: are random vectors.

- Mutation: Mutation operator causes variations on the values of a number of chromosomes in the population (determined as $P_m \times N$, where P_m and N: are the probability of the mutation and the population size, respectively). Let $\vec{X}_i(t)$ a randomly selected chromosome, and then the mutation formulation is defined as:

$$\vec{X}_i(t+1) = \vec{X}_i(t) + \left(\vec{b} \times \eta\right) \qquad (2)$$

where $\vec{b} \in [0,1]^D$: is a random vector and η is a constant value (Mahmoodabadi and Nemati, 2016).

Group Search Optimization

The Group Search Optimization algorithm (GSO) inspired by animal behavior was suggested by He et al. (He et al., 2006, 2009). GSO uses the Producer-Scrounger model (PS) as a framework. The PS model is based on the social foraging strategies of groups living animal. 1) Producing (searching for food); and 2) Joining (joining resources discovered by others) are two nutritional strategies in the group. Basically, GSO is a population-based optimization algorithm. In GSO algorithm, the population is called the group, and each individual in the population is called a member. In an n-dimensional search space, the i^{th} member in the k_{th} search space has a current position $X_i^k \in R^n$ and a head angle $\phi_i^k = \left(\phi_{i1}^k,...,\phi_{i(n-1)}^k\right) \in R^{n-1}$ and a head direction $D_i^k\left(\varphi_i^k\right) = \left(d_{i1}^k,...,d_{in}^k\right) \in R^n$ is defined by the following equation:

$$d_{i1}^k = \prod_{p=1}^{n-1} cos\left(\phi_{ip}^k\right) \tag{3}$$

$$d_{ij}^k = sin\left(\phi_{i(j-1)}^k\right)\prod_{p=i}^{n-1} cos\left(\phi_{ip}^k\right) \tag{4}$$

$$d_{in}^k = sin\left(\phi_{i(n-1)}^k\right) \tag{5}$$

In the GSO algorithm, a group is consist of three types of members: producer, scroungers and rangers. Producer and scroungers behavior is based on the PS model, but rangers are used with random behavior to avoid entrapment at the local minimum. In the GSO algorithm, for accuracy and convenience in calculations, only one producer is considered in each replication, and the rest of the remaining members are assumed to be scroungers and ranger type. During each iteration, a member of the group is placed in the most satisfactory region and obtains the best value of the target function, which this member is considered as the producer, and then the scroungers search environment (optimal amount) is examined. The scanning can be done through physical contact, visual, chemical or auditory mechanisms. The visual scanning is the main mechanism for scan by many species of animals, where is used by the producer in the GSO. In optimization problems of more than three dimensions, the visual scan is extended to a n-dimensional space, which is determined by the maximum pursuit angle $\theta_{max} \in R^{n-1}$ and the maximum pursuit distance $l_{max} \in R^1$ in the three-dimensional space. These parameters are shown in Figure 1.

In the GSO algorithm, the k_{th} iteration of the behavior of the producer X_p will be as follows:

1. The producer will scan zero degree and then randomly scan three points in space, which are:

one point at zero degree:

$$X_z = X_p^k + r_1 l_{max} D_p^k\left(\phi^k\right) \tag{6}$$

A point on the right of the hypercube:

$$X_r = X_p^k + r_1 l_{max} D_p^k\left(\phi^k + r_2\theta_{max}/2\right) \tag{7}$$

A point on the left of the hypercube:

$$X_l = X_p^k + r_1 l_{max} D_p^k\left(\phi^k + r_2\theta_{max}/2\right) \tag{8}$$

where $r_1 \in R^1$: is a random number with a normal distribution with the mean of 0 and the standard deviation of 1 and $r_2 \in R^{n-1}$ is the random sequence in the range (0, 1).

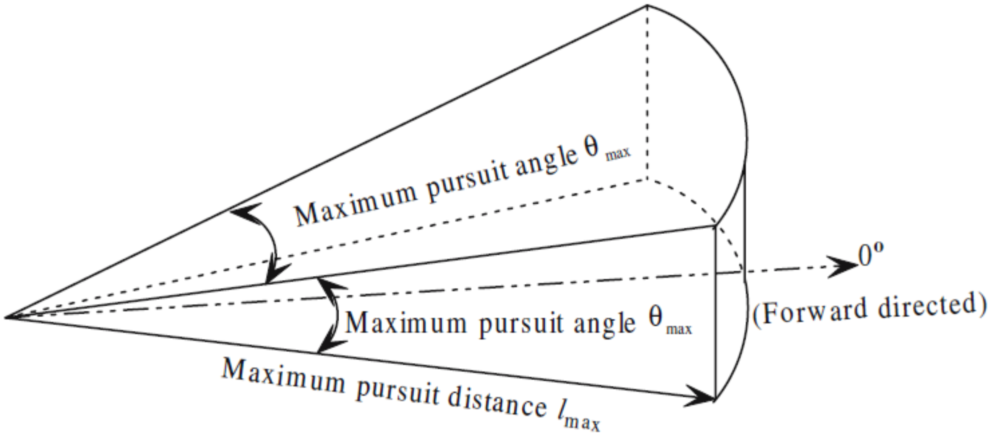


Fig. 1. Scanning field in 3D space

2. Then the producer will find the best point and the best resource. If the best point had a better resource than its current position, it flies toward that source. Otherwise, it stays in its current position and moves to a new angle:

$$\phi^{k+1} = \phi^k + r_2\alpha_{max} \tag{9}$$

where α_{max}: is the maximum turning angle.

3. If the producer can't find a better area after an iteration, then it returns to zero degree:

$$\phi^{k+a} = \phi^k \tag{10}$$

where a: is a constant that is obtained by round $\sqrt{n+1}$.

In each iteration, some of the members of the group are selected as scrounger. In the k_{th} iteration, the behavior of the i^{th} scrounger, can be modeled as a random walk towards the producer:

$$X_i^{k+1} = X_i^k + r_3\left(X_p^k - X_i^k\right) \tag{11}$$

where $r_3 \in R^n$: is a uniform random sequence in the range (0, 1).

In the GSO algorithm, random walks, which is one of the most efficient way to search for sources with random distribution, is used by rangers. If the i^{th} member of the group is chosen as a ranger, in k^{th} repeating, this ranger produces a random angle and a random distance l_i accordance to the following relations:

$$\phi_i^{k+1} = \phi_i^k + r_2\alpha_{\max} \tag{12}$$

$$l_i = a.r_1 l_{\max} \tag{13}$$

and moves to a new position using the following equation (He et al., 2006).

$$X_i^{k+1} = X_i^k + l_i D_i^k\left(\phi^{k+1}\right) \tag{14}$$

FORMULATION OF VERTICAL ALIGNMENT OPTIMIZATION

Figure 2 represent the typical highway longitudinal profile. In this figure, the existing ground has been shown by dashed line and vertical alignment with some PVIs has been drawn up by solid line. The ith PVI is identified by x^i_{PVI}, y^i_{PVI} and L^i_{PVI} where these parameters indicate the station, elevation and vertical curve length, in the respective order. The value of L^i_{PVI} for i = 1 and i = n was regarded zero.

Furthermore, station, elevation and minimum allowable height of ith compulsory point are depicted as x^i_{Brg}, y^i_{Brg} and h^i_{Brg}, respectively.

Objective Function

In this research, four different objective functions have been utilized for optimization of vertical alignment. Table 2 presents the considered objective functions used in this work.

Table 2. The considered Objective functions in this research

Objective function	Unit	Formulation
The sum of the absolute value of difference between the vertical alignment and the existing ground	(m)	$F1 = \sum_{i=1}^{n} \left\lvert y^i_{EG} - y^i_{FG} \right\rvert$
The sum of the absolute value of difference between the vertical alignment and the existing ground with respect to different weights for cuts and fills	($/m^2)	$F2 = \alpha \times \sum_{i=1}^{n_c} \left\lvert y^i_{EG} - y^i_{FG} \right\rvert + \beta \times \sum_{j=1}^{n_f} \left\lvert y^j_{FG} - y^j_{EG} \right\rvert$
The sum of cut and fill volumes	m^3	$F3 = V_c + V_f$
Total Earthwork cost	($)	$F4 = \delta_1 \times C_c \times V_c + \delta_2 \times C_f \times V_f$

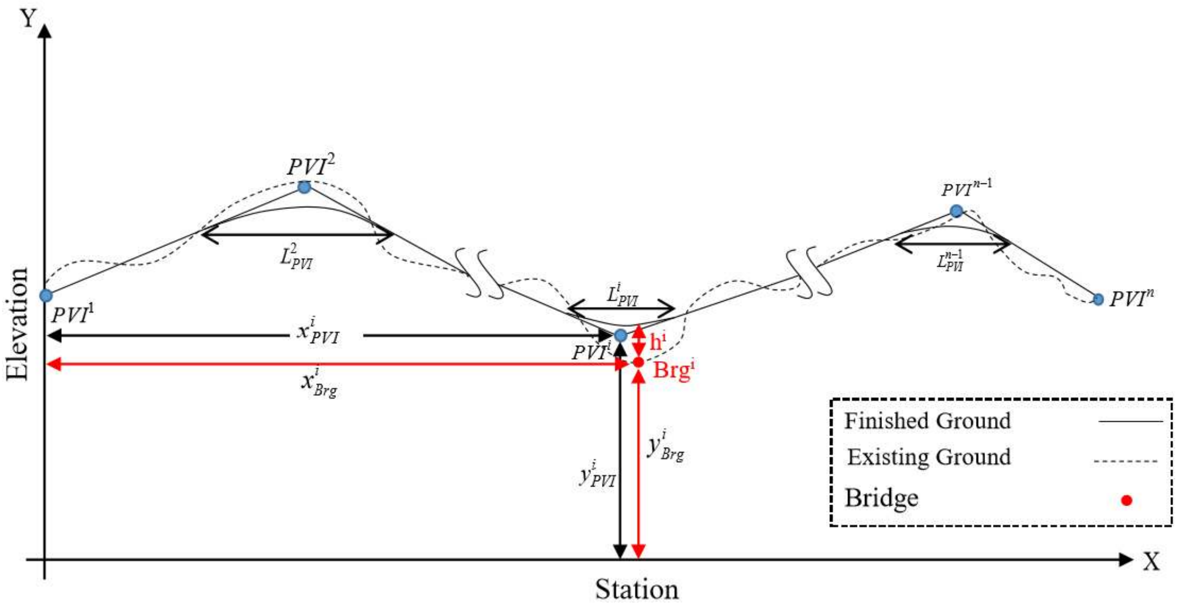


Fig. 2. A part of the longitudinal profile for a road

In Table 4, F1 to F4 are the objective functions; y^i_{EG}: is the height of the existing ground for ith point, y^i_{FG}: is the height of the vertical alignment (finished ground) for ith point, *n*: is the number of existing ground points; *α* and *β*: are weights for cutting and filling, respectively; n_c: is the number of existing ground points located in the cut; n_f: shows the number of existing ground points located in the fill; δ_1: denotes the swelling factor; δ_2: denotes the shrinkage factor; C_c: denotes the cutting cost per m^3; C_f: denotes the filling cost per m^3; V_c: denotes the cutting volumes in m^3, and V_f : denotes filling volumes in m^3.

To determine the Earthwork volume, it is necessary to calculate the fill and cut areas for two successive sections first; and then, the prismoidal formula is used to calculate the Earthwork volume. In this research, the developed program uses the coordinate method to calculate the fill and cut areas for each section. Following the calculation of fill and cut areas, the Earthwork volume between two successive sections can be calculated by applying the presmoidal approach. The prismoidal formulation for computation of cut or fill volumes is as follows:

$$V = \frac{A_1 + A_2 + \sqrt{A_1 A_2}}{3} L \tag{15}$$

where *V*: shows the volume between two successive sections; A_1: represents the area of the first section; A_2: represents the area of the second section, and *L*: denotes the horizontal distance between two successive sections. As shown in Figure 3, the fill and cut volumes between two consecutive sections is calculated according to the fill and cut conditions for two successive sections.

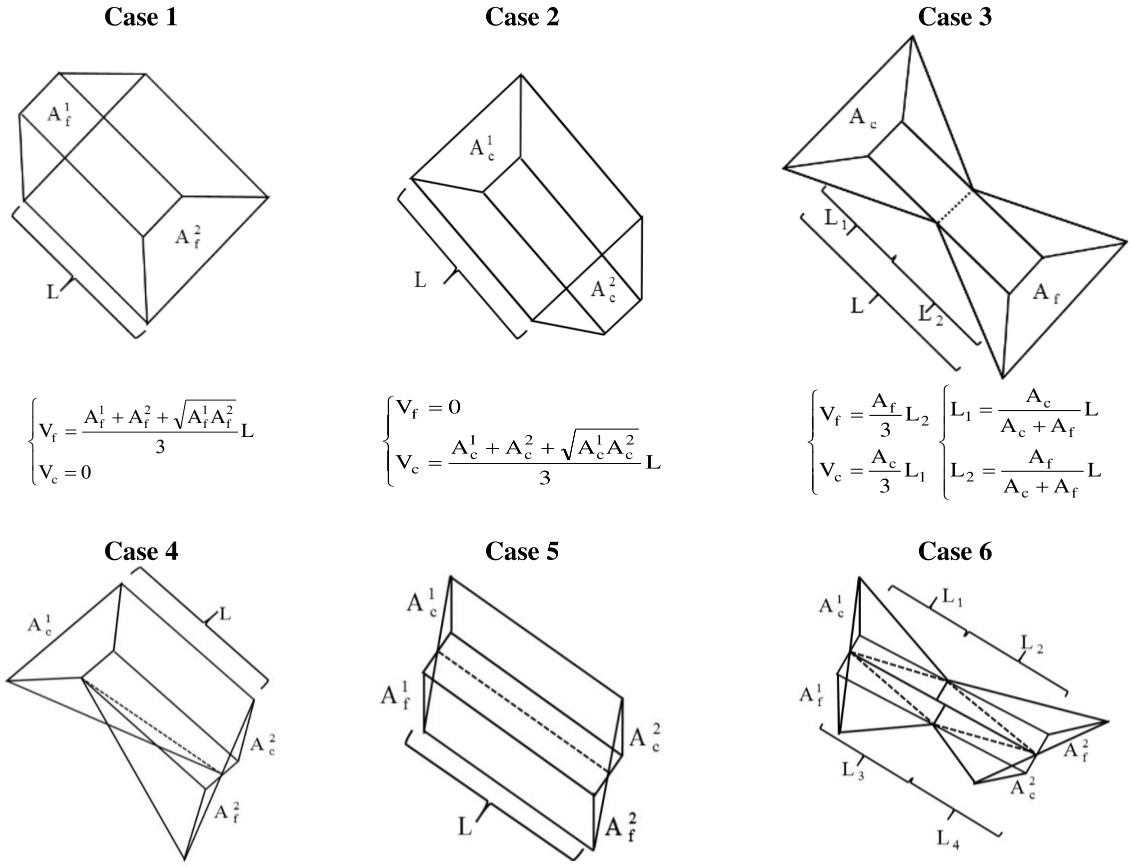
Constraints

Grade of Tangents

The topography of land, highway category, the traction power of heavy vehicles, safety, construction costs, drainage considerations, and landscape liniment are different parameters that dictate the maximum and minimum grade of tangents in vertical alignment (IMPO, 2012; AASHTO, 2011).

The grade of tangents should not surpass the minimum and maximum allowable values as the following:

$$g_{\min} \le g^i = \frac{y^{i+1}_{PVI} - y^i_{PVI}}{x^{i+1}_{PVI} - x^i_{PVI}} \le g_{\max}; \; i = 1, 2, \ldots, N-1 \tag{16}$$



Case 1:

$$\begin{cases} V_f = \dfrac{A_f^1 + A_f^2 + \sqrt{A_f^1 A_f^2}}{3} L \\ V_c = 0 \end{cases}$$

Case 2:

$$\begin{cases} V_f = 0 \\ V_c = \dfrac{A_c^1 + A_c^2 + \sqrt{A_c^1 A_c^2}}{3} L \end{cases}$$

Case 3:

$$\begin{cases} V_f = \dfrac{A_f}{3} L_2 \\ V_c = \dfrac{A_c}{3} L_1 \end{cases} \quad \begin{cases} L_1 = \dfrac{A_c}{A_c + A_f} L \\ L_2 = \dfrac{A_f}{A_c + A_f} L \end{cases}$$

Case 4:

$$\begin{cases} V_f = \dfrac{A_f^2}{3} L \\ V_c = \dfrac{A_c^1 + A_c^2 + \sqrt{A_c^1 A_c^2}}{3} L \end{cases}$$

Case 5:

$$\begin{cases} V_f = \dfrac{A_f^1 + A_f^2 + \sqrt{A_f^1 A_f^2}}{3} L \\ V_c = \dfrac{A_c^1 + A_c^2 + \sqrt{A_c^1 A_c^2}}{3} L \end{cases}$$

Case 6:

$$\begin{cases} V_f = \dfrac{A_f^1 L_3}{3} + \dfrac{A_f^2 L_2}{3} \\ V_c = \dfrac{A_c^1 L_1}{3} + \dfrac{A_c^2 L_4}{3} \end{cases} \quad \begin{cases} L_1 = \dfrac{A_c^1}{A_c^1 + A_f^2} L \\ L_2 = \dfrac{A_f^2}{A_c^1 + A_f^2} L \\ L_3 = \dfrac{A_f^1}{A_f^1 + A_c^2} L \\ L_4 = \dfrac{A_c^2}{A_f^1 + A_c^2} L \end{cases}$$

Fig. 3. Computation of fill and cut volumes in terms of fill and cut conditions

Minimum Length of the Vertical Curves

Changing of the longitudinal grade is gradually performed using the vertical curves. Actually, the vertical curve must fulfill the acceptable sight distance, drainage of surface water, safety, driver comfort and visual aesthetic of the highway. Normally, the minimum sight distance for safe driving is used to calculate the minimum acceptable length of vertical curves (IMPO, 2012; AASHTO, 2011). The minimum acceptable length of the vertical curve should satisfy the following relation:

$$L_i \geq k \times A_i \; ; \; i = 2,3,\ldots,N-1 \qquad (17)$$

$$A_i = \left| \frac{y_{PVI}^{i+1} - y_{PVI}^{i}}{x_{PVI}^{i+1} - x_{PVI}^{i}} - \frac{y_{PVI}^{i} - y_{PVI}^{i-1}}{x_{PVI}^{i} - x_{PVI}^{i-1}} \right| ; i = 2,3,\ldots,N-1 \qquad (18)$$

where *N*: shows the number of vertical alignment PVIs, L_i: shows the length of the vertical curve at i^{th} PVI, A_i: denotes the absolute variance between intersecting tangent grades at i^{th} PVI and *k*: shows the curvature value of the vertical curve for one percent of the grade difference. Other parameters are illustrated in Figure 2. The value of *k* is dependent on the design speed and the type of the vertical curve (sag or crest). Table 3 gives the *k* values for design of vertical curves based on stopping sight distance.

Table 3. *k* values for design of vertical curves (IMPO, 2012)

Design speed (Km/h)	***k* for crest curve**	***k* for sag curve**
50	7	13
60	11	18
70	17	23
80	26	30
90	39	38
100	52	45
110	74	55
120	95	63
130	124	73

Non-Overlapping of Two Successive Vertical Curves

In order to increase the safety and comfort, the final length of vertical curves is fixed to a value more than the minimum acceptable length. It is possible to increase the length of vertical curves to the extent that the overlap between two consequent vertical curves is eliminated to keep the vertical alignment continuous. Henceforth, the optimum vertical alignment should meet the following equation.

$$\left(x_{PVI}^{i+1} - x_{PVI}^{i}\right) > \left(\frac{L_{PVI}^{i+1} + L_{PVI}^{i}}{2}\right);\ i = 2,3,...,N-2 \tag{19}$$

where x_{PVI}^{i} and L_{PVI}^{i}: show the station and vertical curve length for ith PVI.

Compulsory Points

Compulsory points should often be taken into account for designing the vertical alignment. In this study, bridges are supposed as compulsory points having fixed station and a minimum value of the free height. The hydrological studies are used to calculate the station and minimum free height of bridges. The minimum elevation of vertical alignment at the bridge's station can be stablished by the elevation of existing ground point plus the minimum acceptable free height of bridge at the desired station.

COMPUTER PROGRAM FOR OPTIMIZATION OF THE VERTICAL ALIGNMENT

A computer program was implemented in the MATLAB 2014 to estimate the earthwork volumes, exactly. This program is made of three main parts. In the first part, station, elevation, and length of the vertical curve for each PVI as well as the cross section data such as station, offset and elevation of the ground points are imported from text files. Then, the elevation of the vertical alignment matching each cross section is calculated. In the second part, the coordinate method is implemented along with the cross section points, vertical alignment elevations as well as typical section (travel way wide, shoulder wide, slope of travel way, slope of shoulder, cutting slope, filling slope, trench depth and trench wide) to calculate the filling and cutting area for each section.

In the third part, filling and cutting volumes between consequent cross sections and finally total filling and cutting volumes for the highway are calculated with considering to the situation of the two consequent cross-sections as well as the filling and cutting area obtained from the second part. One of the reliable softwares for highway geometric design is AutoCAD Land Desktop 2009 developed by Autodesk, Inc.

In this study, in order to validate the developed program, the earthwork volumes calculated by the AutoCAD Land Desktop 2009 were compared with the results of developed code for three different highways. Validation results are presented in Table 4.

As it can be observed, the earthwork volumes calculated using the two program are much closed, and the differences are very small. Hence, the developed MATLAB 2014 code has an acceptable ability for computation of earthwork volumes. Figure 4 illustrates the optimization process schematically. The optimization program receives the text files corresponding to the cross sections, vertical alignment and bridge information as well as the parameters for optimization such as upper and lower bounds of the decision variables, internal parameters of optimization algorithm, number of initial population and maximum number of iterations.

At the first iteration of the optimization algorithm, after generation of random solution, the initial vertical alignment would be replaced by one of solutions. Then, the objective functions corresponding to the solution are identified and the final values of the objective functions are determined based on the constraints and with respect to the penalty approach. In the other iterations, the optimization algorithm optimizes the solution until the stopping criteria satisfy.

Table 4. Comparison of Earthworks computed by AutoCAD Land Desktop and developed code

Earthwork type	**Method**	**Topography of highway**		
		Level	**Rolling**	**Mountain**
Cut volume (m^3)	AutoCAD Land Desktop	2056.21	550845.33	277.82
	Developed Code	2002.97	547963.94	263.43
	Difference (%)	2.59	0.53	5.17
Fill volume (m^3)	AutoCAD Land Desktop	80539.69	154396.7	92150.09
	Developed Code	80317.97	153395.99	91346.86
	Difference (%)	0.28	0.65	0.87

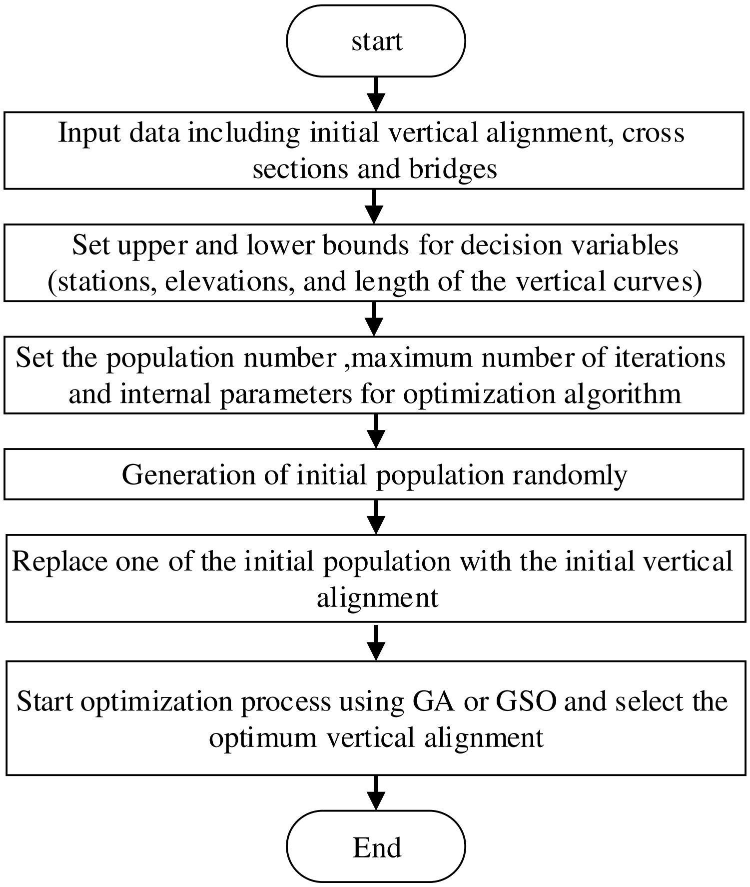


Fig. 4. Optimization process

EFFECT OF OBJECTIVE FUNCTION ON THE EARTHWORK COST

Design of Highways

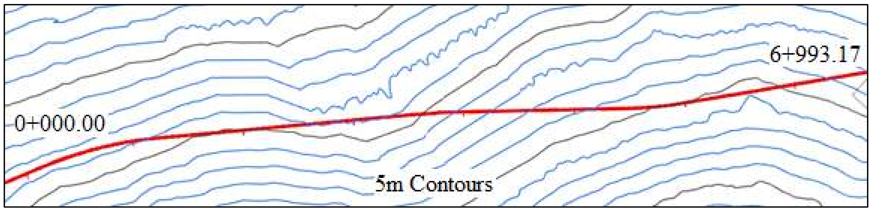
To evaluate how the objective function influences the earthwork cost optimization, three highways were designed with three diverse topographies (level, rolling, and mountainous terrain).

The geometric design criteria for each terrains are given in Table 5. Horizontal alignment of three paths in level, rolling and mountainous terrains has been illustrated in Figure 5. The considered parameters for calculation of the objective function are listed in Table 6.

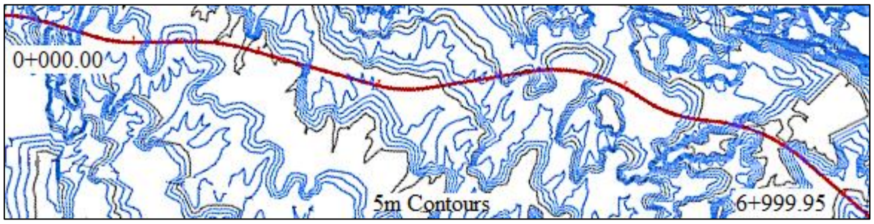
Following the design of highways by AutoCAD Land Desktop 2009 software, an expert highway engineer designed a preliminary vertical alignment based on the design restrictions. Then, the vertical alignment data including station, elevation and vertical length curve of PVIs and cross section data including offset and elevation of existing ground points as well as station, elevation and free height of bridges were exported into text files. These files are input files for the MATLAB 2014 optimization program.

Setting the Parameters of the Optimization Algorithms

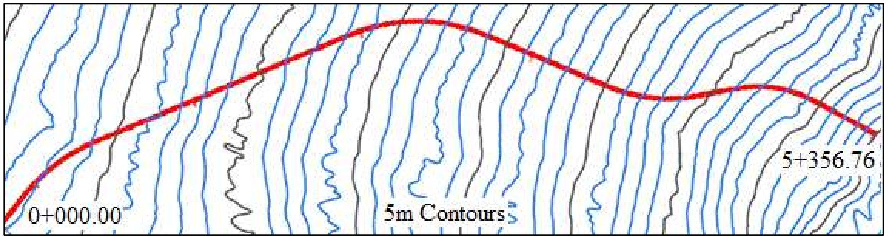
For the genetic algorithm, the changing range of the crossover and mutation probabilities were regarded in [0.7-1] and [0.1-0.4], respectively. The optimum vertical alignment of a level highway with population 50 and generation 2000 and the first objective function was considered to select the best values of these two parameters. After a try and error processes the best values for crossover and mutation probabilities were identified as 0.9 and 0.4, respectively. The Group Search Optimization (GSO) algorithm consists of three design parameters of α_{max}, I_{max} and θ_{max} that for each one, a random vector was set between 0 and 1 witch their values variate in each repetition.



(a) Level Terrain



(b) Rolling Terrain



(c) Mountainous Terrain

Fig. 5. Existing paths in level, rolling and mountainous terrains

Table 5. Geometric design criteria for design of highways in level, rolling and mountainous terrains

Design parameters	Level	Rolling	Mountain
Classification of highway	Major road	Major road	Major road
Designing speed (km/h)	110	100	100
length of alignment (m)	6993.17	6999.95	5356.76
Road width (m)	11	11	11
Filling slope (vertical to horizontal)	2:3	2:3	2:3
Cutting slope (vertical to horizontal)	1:1	1:1	1:1
trench depth (m)	0.8	0.8	0.8
trench wide (m)	0.6	0.6	0.6
Slope of travel way (%)	2	2	2
Slope of shoulder (%)	2	2	2
The number of compulsory points	9	4	7
The number of PVIs	9	11	8
The number of decision variables	21	27	18
The maximum grade of tangents (%)	3	5	6
The minimum grade of tangents (%)	0	0.3	0.3
K value for sag vertical curves	74	52	52
K value for crest vertical curves	55	45	45
The minimum free height of bridges (m)	0.4	2	1.5

Table 6. Assumed values of parameters for computation of objective functions

Parameters	Value
α (\$/m^3)	0.26
β(\$/m^3)	0.32
C_C (\$/m^3)	0.26
C_F (\$/m^3)	0.32
δ_1	1
δ_2	1

1$=100000 Rials

Comparison of the Optimization Algorithms from Point of View of Optimum Value of the Objective Function

The optimum vertical alignment for each highways were determined based on four different objective functions and with initial population 50 and maximum iterations of 2000 using genetic algorithm and group search optimization. The upper and lower bounds of the elevation were considered as 20m. The upper and lower bounds of the station were regarded as the half distance between the considered PVI and previous and next PVIs. The obtained results are depicted for three highways in level, rolling and mountainous in Tables 7-9, respectively. For each case, after determination of the optimum vertical alignment based on the considered objective function, the optimality percentage of each algorithm was obtained.

Regarding to these tables, the Group Search Optimization algorithm has more ability to find global optimum solution for all topographies and all objective functions in comparison with the genetic algorithm. The optimality percentage of the group search algorithm for the objective function F4 is 45.2, 15.26 and 22.19 for level, rolling and mountainous terrains, respectively, while these values for the genetic algorithm are 19.42, 8.37 and 6.11, respectively. Figures 6 through 8 illustrate the optimality percentage of each objective function obtained by the genetic algorithm and group search algorithm for three topographies.

Also, Figures 9-11 depict the optimality graphs of four objective functions for topography of level, rolling and mountains, respectively. Obviously, the genetic algorithm gets trapped in local optima and cannot converge to the global optimum solution, whereas the group search algorithm converges to the global optimum solution with a suitable number of iterations.

Table 7. Initial and optimized objective function values for highway designed in the level terrain

Objective function	Manual	GA	GA optimality percentage	GSO	GSO optimality percentage
F1 function values (m)	904.87	785.44	13.2	518.39	42.71
F2 function values ($/m^2)	289.6	251.2	13.26	162.9	43.74
F3 function values (m^3)	122346.27	102624.74	16.12	68375.65	44.11
F4 function values ($)	39113	31517.6	19.42	21433	45.2

Table 8. Initial and optimized objective function values for highway designed in the rolling terrain

Objective function	Manual	GA	GA optimality percentage	GSO	GSO optimality percentage
F1 function values (m)	2877.81	2412.42	16.17	2195.43	23.71
F2 function values ($/m^2)	875.2	683.3	21.93	619.9	29.17
F3 function values (m^3)	670590.99	637124.37	4.99	581757.52	13.25
F4 function values ($)	196761.2	180289.6	8.37	166743	15.26

Table 9. Initial and optimized objective function values for highway designed in the mountainous terrain

Objective function	Manual	GA	GA optimality percentage	GSO	GSO optimality percentage
F1 function values (m)	463.22	437.35	5.58	359.26	22.44
F2 function values ($/m^2)	14.82	13.98	5.66	11.27	23.95
F3 function values (m^3)	91761.6	86104.8	6.16	72629.02	20.85
F4 function values ($)	29333.2	27541.2	6.11	22824.6	22.19

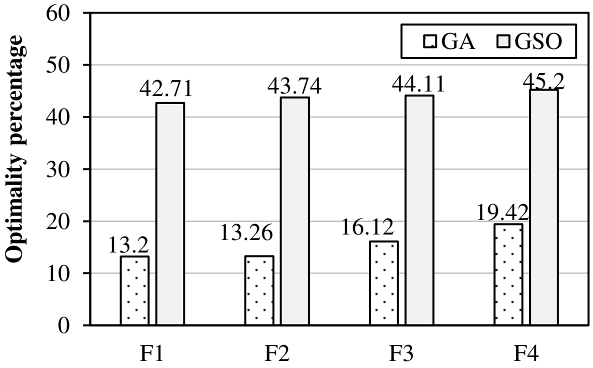


Fig. 6. Optimality percentage in level terrain

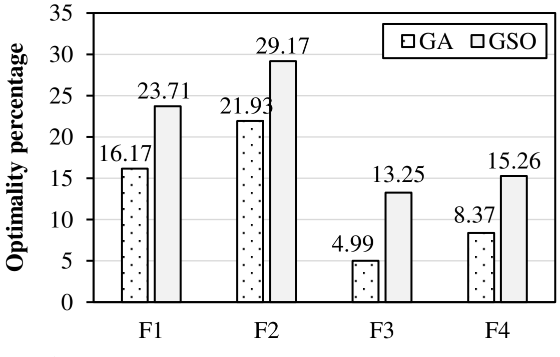


Fig. 7. Optimality percentage in rolling terrain

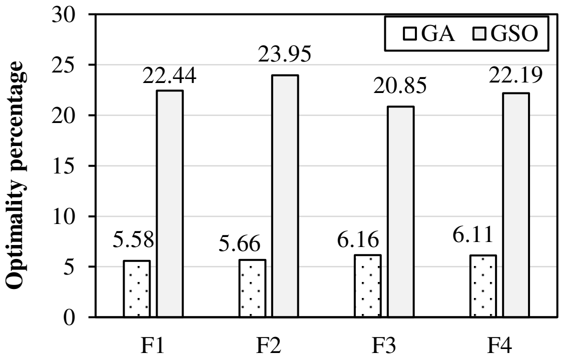
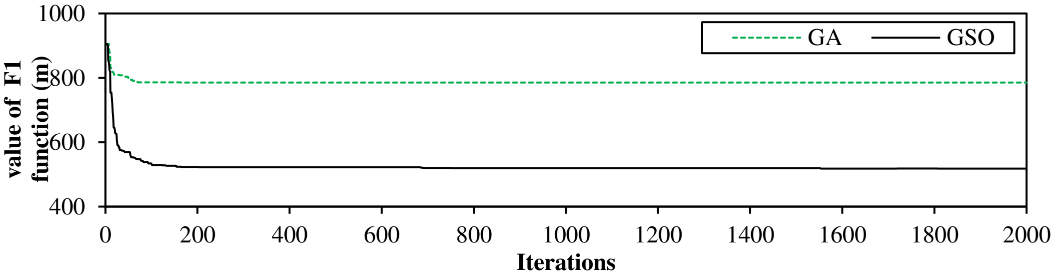
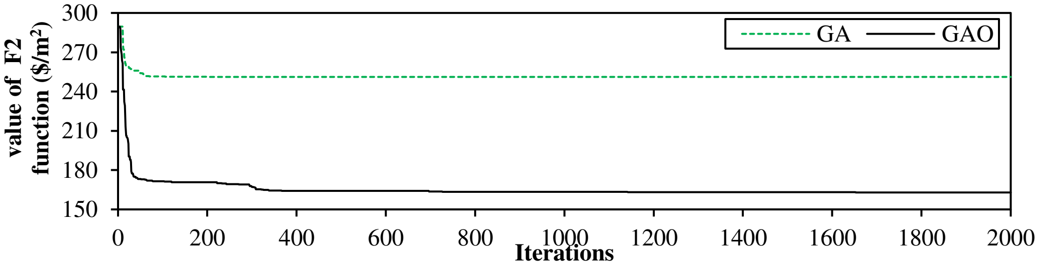


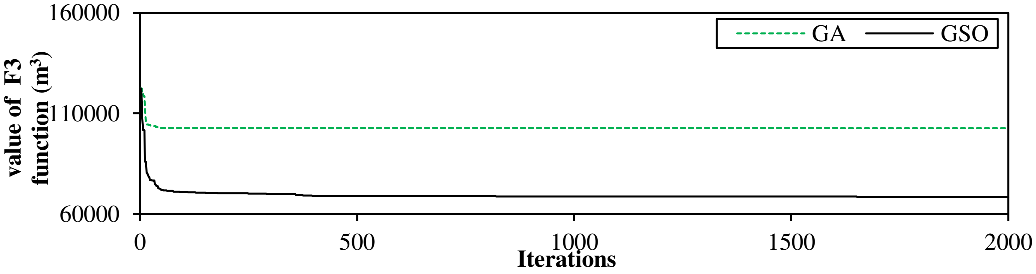
Fig. 8. Optimality percentage in mountain terrain



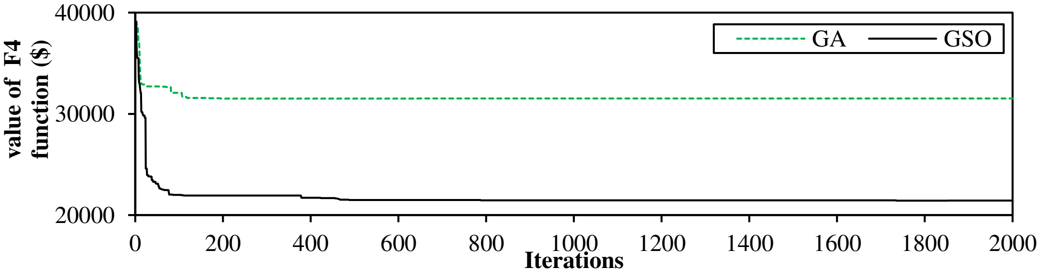
(a) F1 function values



(b) F2 function values

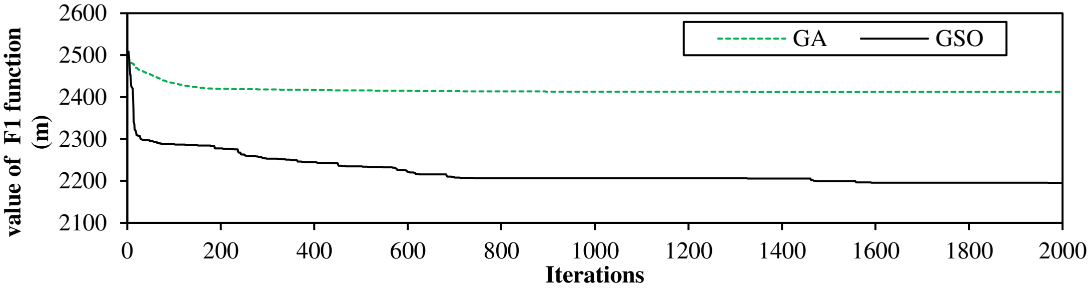


(c) F3 function values

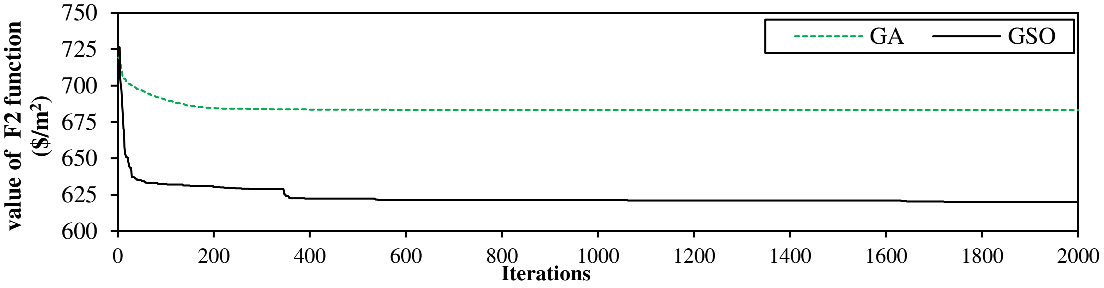


(d) F4 function values

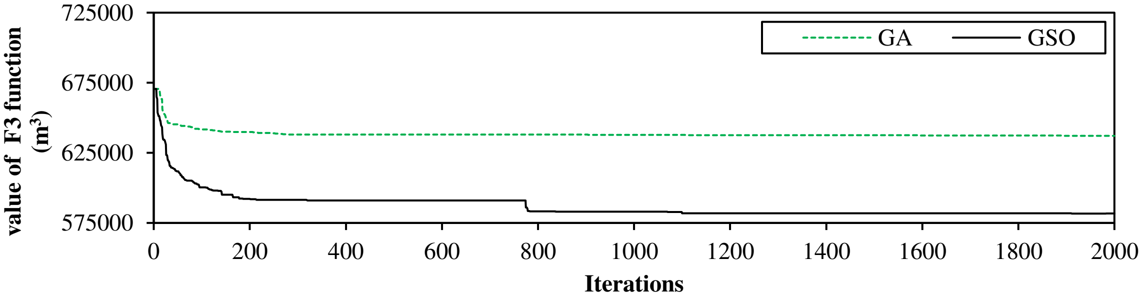
Fig. 9. Performance of different algorithms to find optimum solution (level terrain)



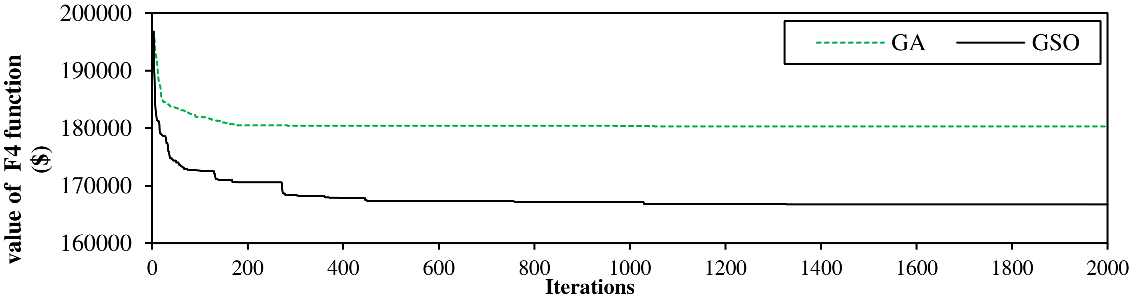
(a) F1 function values



(b) F2 function values

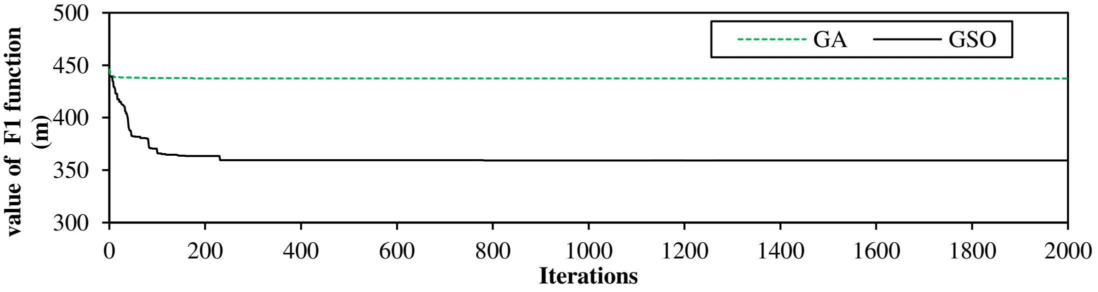


(c) F3 function values

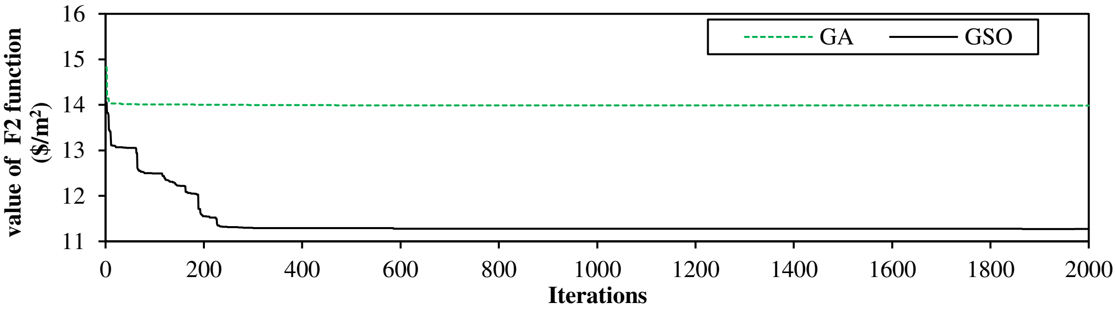


(d) F4 function values

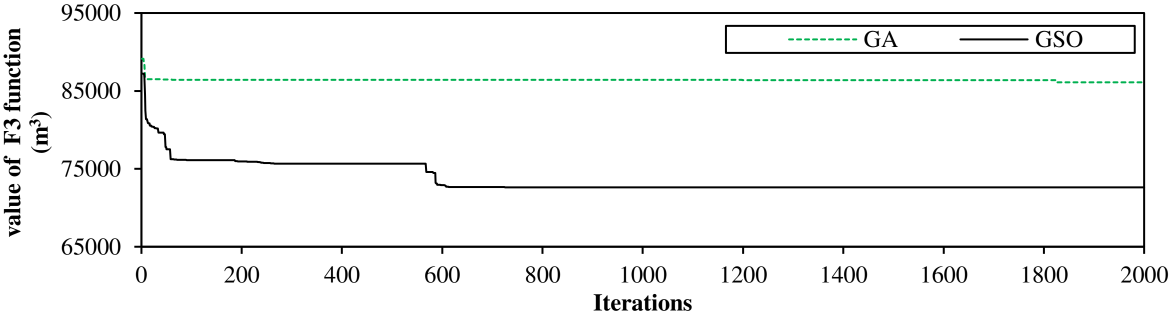
Fig. 10. Performance of different algorithms to find optimum solution (rolling terrain)



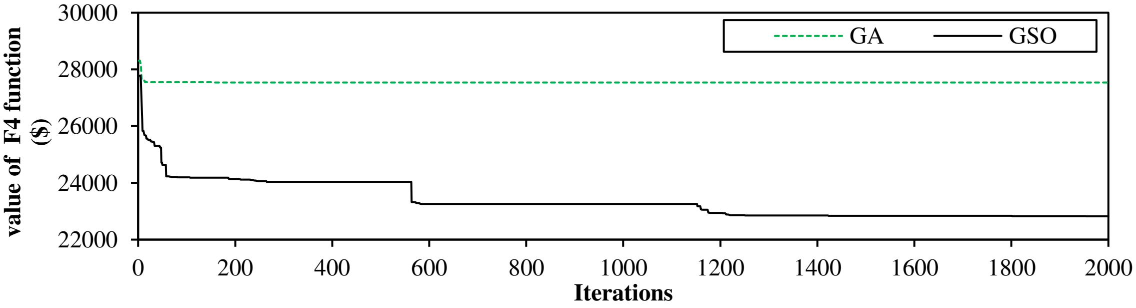
(a) F1 function values



(b) F2 function values



(c) F3 function values



(d) F4 function values

Fig. 11. Performance of different algorithms to find optimum solution (mountainous terrain)

To evaluate the performance of Ga and GSA algorithms, run time for each repetition and repetitions to find optimum solution are presented in Figures 12 and 15, in the respective order.

According to Figures 12 and 13, the required run time for the GSO is less than that of the genetic algorithm in case of all terrains. Furthermore, the run time of objective function F3 and F4 is approximately equal and several times more than that for objective functions F1 and F2 in all terrains. Moreover, it can be seen that the run time of objective function F1 is approximately half of that for objective function F2. In the maximum state when using genetic algorithm, the run time of F4 is 150 times more than that of F1 for the rolling topography. This value for the group search algorithm is about 265.

The first optimum solution for the level topography using the GSO algorithm and for F1, F2, F3 and F4 are respectively is find at iterations 5, 5, 4 and 2, while those for the genetic algorithm are at iterations 8, 11, 5, and 4 for the four objective functions, respectively. In the rolling topography, the first obtained optimum solutions using GSO and for F1, F2, F3 and F4 are respectively at iteration of 1, 1, 6 and 4, while those for the genetic algorithm are at iterations 1, 1, 13, and 3 for the four objective functions, respectively. In the mountainous terrain, the

GSO algorithm found the first optimum solutions at the first iteration for all four objective functions, while the genetic algorithm found those at iterations 1, 3, 1 and 1, respectively. Figures 14 and 15 demonstrate that the genetic algorithm after a limit number of the iterations gets trapped in the local optima and couldn't find the global optimum solution.

Comparison of the Objective Functions in Terms of Earthwork Cost Reduction

The main objective of optimization of a vertical alignment is finding a vertical alignment that implies the minimum earthwork cost of the project. Hence, other objective functions (F1 to F3) would be considered when they can reduce the earthwork cost to the minimum level. In order to evaluate this issue, the Earthwork cost (the F4 objective function) is calculated for the optimized vertical alignments based on the other objective functions. Tables 10-12 depicted the earthwork cost values for three terrains obtained by GA and GSO.

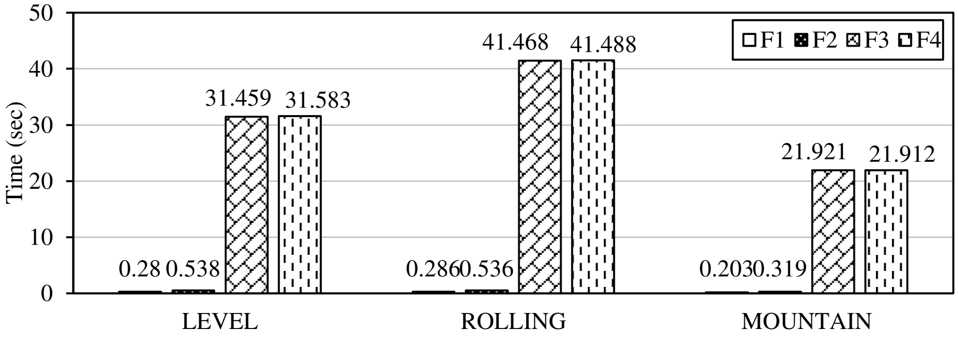


Fig. 12. Run time for each iteration in case of GA algorithms

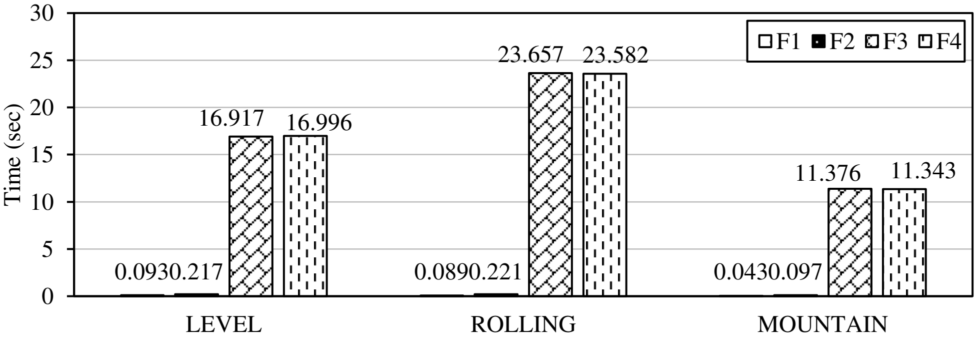


Fig. 13. Run time for each iteration in case of GSO algorithms

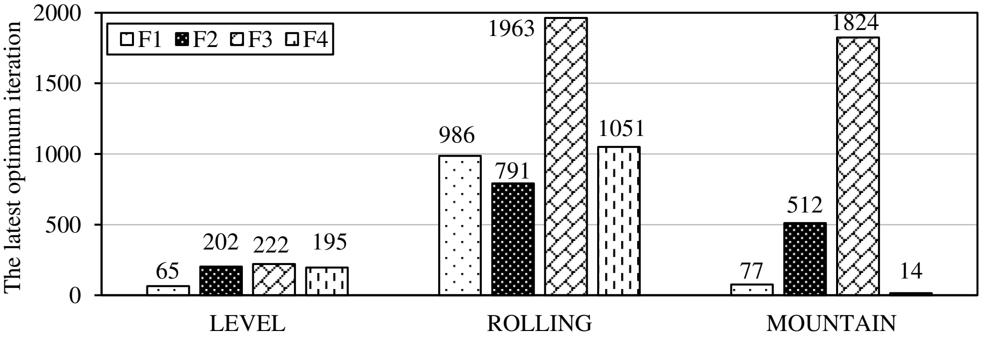


Fig. 14. The latest optimum iteration in case of GA algorithms

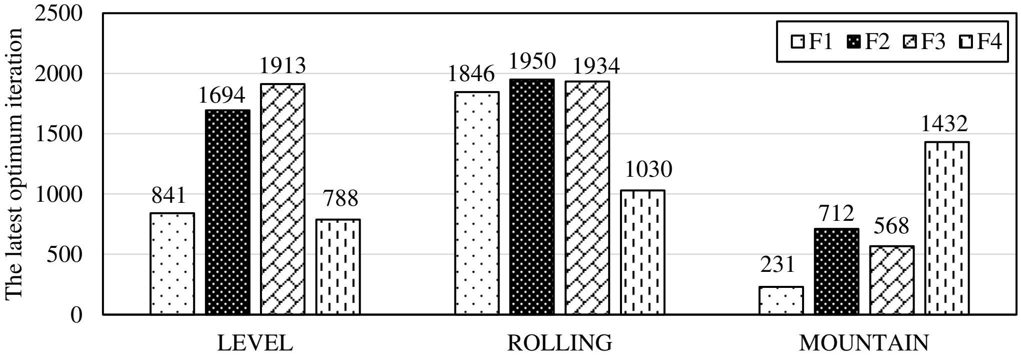


Fig. 15. The latest optimum iteration in case of GSO algorithms

Table 10. Earthwork cost for optimized vertical alignments in level terrain

Objective function	Manual	GA	GSO
F1 ($)	39113	31624.2	22776.6
F2 ($)	39113	31621.6	23516.6
F3 ($)	39113	32668.2	21453.2
F4 ($)	39113	31517.6	21433

Table 11. Earthwork cost for optimized vertical alignments in rolling terrain

Objective function	Manual	GA	GSO
F1 ($)	196761.2	194347	189139.6
F2 ($)	196761.2	212319.2	205724.2
F3 ($)	196761.2	181901.2	167397
F4 ($)	196761.2	180289.6	166743.2

Table 12. Earthwork cost for optimized vertical alignments in mountain terrain

Objective function	Manual	GA	GSO
F1 ($)	29333.2	27886	22856.4
F2 ($)	29333.2	27581	22845.6
F3 ($)	29333.2	27562.4	22906.4
F4 ($)	29333.2	27541.2	22824.6

As it is expected, the objective function F4 obtained less Earthwork cost values in comparison with other three objective functions. Figures 16 and 17 respectively show the optimality of the earthwork cost for the vertical alignment obtained from different objective functions and by two optimization algorithms.

The ground line, the preliminary vertical alignment, as well as optimal vertical alignment for GSO algorithm in three different terrains of level, rolling and mountainous are presented in Figures 18 through 20 in the respective order. As shown, the objective functions F3 and F4 is very close in terms of the optimality percentage. In other words, regarding the minimization of the earthwork cost (4th objective function), pretty close results can be expected by minimizing either the sum of cut and fill volumes (3rd objective function) or the Earthwork cost (4th objective function).

The optimality percentage of objective functions F1 and F2 is greatly dependent to the condition of the highway cross sections. For instance, in this research, it can be observed that in the highways designed in the level and mountain terrains, objective function F1 and F2 are able to find optimum vertical alignment in terms of Earthwork cost, while for the rolling topography, these objective functions cannot find the vertical alignment with the minimum Earthwork cost.

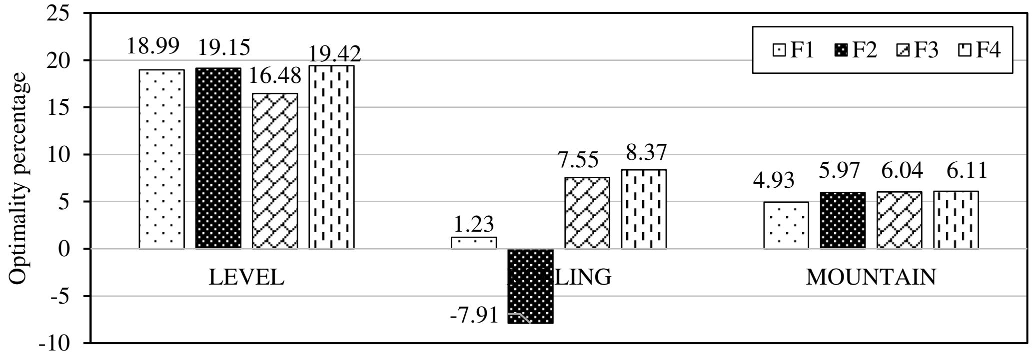


Fig. 16. Optimality percentage of Earthwork cost using genetic algorithm

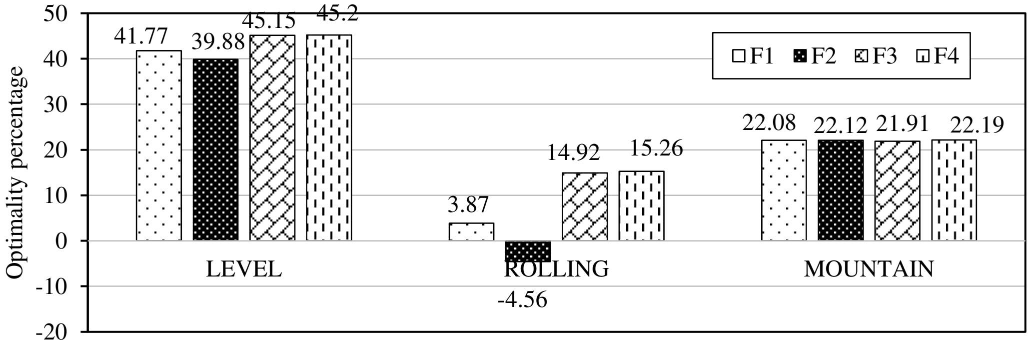


Fig. 17. Optimality percentage of Earthwork cost using group search optimization

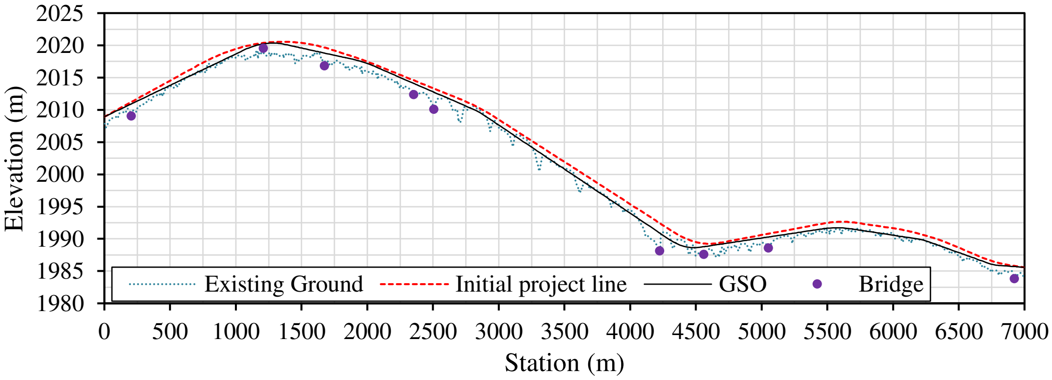


Fig. 18. Longitudinal profile in case of highway designed in level terrain

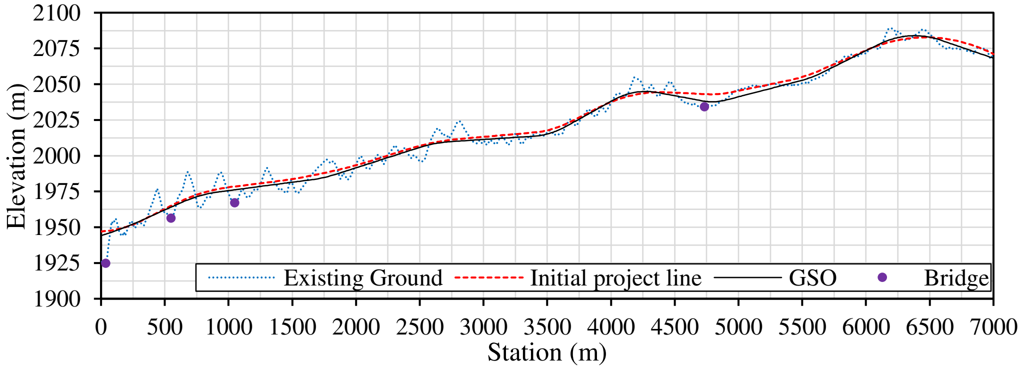


Fig. 19. Longitudinal profile in case of highway designed in rolling terrain

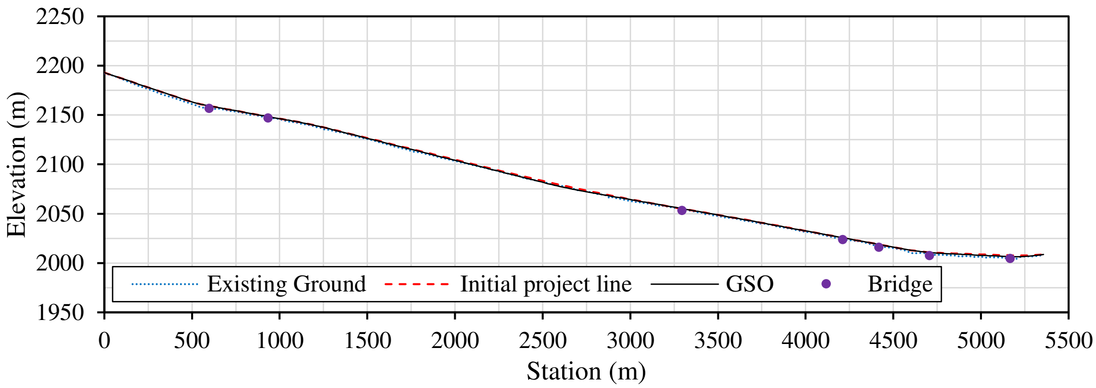


Fig. 20. Longitudinal profile in case of highway designed in mountainous terrain

As shown, for objective function F2, the resulting optimum solution by this objective function leads to increased Earthwork cost. Consequently, it would be necessary to apply earthwork volumes or Earthwork cost as the objective function for optimizing the vertical alignment. Indeed, the Earthwork cost cannot be minimized by designing the vertical alignment as close as possible to the existing ground at the highway centerline.

Results of this study show that the manual design of vertical alignment which considers only the minimizing distance between vertical alignment and ground line at centerline is not able to reach the vertical alignment with minimum earthwork cost. In fact, human design does not have the ability to consider all cross sections for designing an optimal vertical alignment and so the use of computer algorithms for optimizing the project line is very necessary.

This research also confirms that the applying a powerful optimization algorithm such as GSO can improve finding optimum vertical alignment in terms of both optimality percentage as well as run time.

CONCLUSIONS

The aim of this paper was comparing several objective functions for optimization of the highways vertical alignment. These objective functions were considered as the sum of the absolute value of variance between the vertical alignment and the existing ground (F1), the sum of the absolute value of variance between the vertical alignment and the existing ground regarding different weights for cuts and fills (F2), the sum of cut and fill volumes (F3), and the Earthwork cost (F4).

Constraints for this optimization problem were considered as maximum and minimum of tangents grade, minimum elevation of compulsory points, non-overlapping of vertical curves and minimum length of vertical curves. To determine the earthwork volumes precisely, a computer program was implemented in the MATLAB 2014 and then it was validated using AutoCAD Land Desktop 2009. This comparison illustrated that the developed code is able to calculate the highway earthwork volumes with an error about 5%.

Results of this study indicates that contrary to the GA, the GSO algorithm is capable of finding the global optimum solution in all terrains and all objective functions more efficiently. In fact, after a few repetitions, the genetic algorithm gets trapped into the local optima and cannot find the global optimal solution, whereas the GSO algorithm converges to the global optimal solution at an appropriate speed. The run time of the GSO is also less than that of the GA for all terrains.

From the perspective of run time, the run time of objective function F3 and F4 is approximately same and several times more than that for F1 and F2 for both optimization algorithms. The run time of F1 is about half run time of F2. In the most extreme case, the run time of objective function F4 is about 265 times more than that the required run time for objective F1.

Results of this study also show that the vertical alignment resulted from minimizing sum of cut and fill volumes (F3 objective function) is very close to the vertical alignment resulted from minimizing the earthwork cost (F4 objective function).

In general, it can be said that the sum of earthwork volumes or the sum of earthwork costs are the most appropriate objective functions for optimization of vertical alignment. In other words, the earthwork cost cannot be essentially minimized by designing the vertical alignment as close as possible to the existing ground at the highway centerline.

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