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WEIGHTED GROUND LINE BASED OPTIMAL ALIGNMENT OF HIGHWAYS

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Abstract: *Earthwork optimization is of particular importance in highway design process in terms of economical and durational aspects. In this context, the optimal alignment should consider cut and fill balance as well as total earthwork minimization to reduce earthwork based costs. In current practice, common way to optimize the amount of earthwork is to set the grade line as closely as possible to the ground line. Nevertheless, this approach may be misleading since the ground line of the road, which is formed by the centerline, cannot characterize the cross-sectional topography. Therefore, the centerline elevation cannot represent the whole cross section in terms of cut and fill balancing and total earthwork minimization. This is a major drawback especially for projects located in mountainous terrains.*
Weighted Ground Line Method (WGLM) is an alignment optimization technique depending on a hypothetical reference line and considering three basic soil properties, namely swelling potential, compactibility percent, and material appropriateness percentage. It should be noted that all the cut material may not be used as a fill material as a result of the discrepancy between the volume in a cut and the volume in fill after compaction. In addition, excavated material may not be appropriated for to be used as fill. These soil attributes are considered in WGLM with different parameters to achieve realistic earthwork optimization in terms of cut-fill balancing and total earthwork minimization.
Results indicated that the method based on WGLM, fuzzy logic based inference system, and evolutionary computation produces outstanding curve fitting capability for the geometric design of highways. The method can also be used for other alignment problems of civil engineering, such as railways, open canals, and etc.
Key words: *Earthwork, highway alignment, optimization, weighted ground line, fuzzy logic, genetic algorithm.*

INTRODUCTION

Optimal highway geometrical design should meet several design criteria. Basically, after the determination of the functional classification of a highway, following fundamental design controls must be considered: a) Design speed, b) design vehicle, c) traffic volume, and d) maximum grade. After the determination of the fundamental design controls, horizontal and vertical alignment are the major process required for a highway design operation.

In essence, highway alignment is performed for the decision of route location on a topographical map by using several tangents and curves connected to each other. Obviously, the alignment process can be considered in two- or three-dimensional (2-D or 3-D) manner. In 3-D approach, which is necessary for the correct definition of the problem, both horizontal and vertical planes are treated for the determination of the optimal route location in terms of earthwork optimization, expropriation cost reduction, and environmental aspect minimization due to valid design specifications. Nevertheless, 3-D highway alignment is a very complex multi-constrained nonlinear optimization problem including a number of solution alternatives having different aspects. Therefore, a direct searching technique, such as genetic algorithm (GA) and random search, seems necessary to solve highway alignment optimization problem [1-4].

Weighted Ground Line Method (WGLM) is a highway alignment technique primarily focusing on earthwork optimization considering several design constraints and soil parameters [5,6]. The philosophy of WGLM is the consideration of a hypothetical center elevation, namely weighted ground elevation (WGE), for each cross section which balancing cut-fill volumes as well as minimizing total earthwork operations. Consequently, WGE is used for alignment optimization problem instead of the centerline. Additionally, WGLM also utilizes several soil properties to calculate realistic cut and fill volumes. In this context, swell/shrinkage ratio and appropriateness parameter (eliminating unacceptable cut material for use in fill volumes) are also included in the method to model real-life problems better. In order to determine these soil parameters, a fuzzy rule-based system is proposed as a part WGLM [7]. Finally, grade line is established using GA approach as a multiphase curve fitting technique [8].

LITERATURE REVIEW

Highway alignment is a nonlinear multi-constrained and multi-objective optimization problem which is very complex due its specific nature. In addition, there are sophisticated relationships among the design variables which increasing level of nonlinearity and resulting in serious difficulties to characterize the problem with limited amount of design variables. Apart from the complex nature of the problem, the primary target of a highway alignment is to find out optimal design variables minimizing the cost function. It should be noted at this point that if multi-objective decision making is performed, there should be more than one cost function, and optimal variables are selected by considering different cost values. Under the light of these, highway alignment problem is appropriate to be solved with a direct searching technique, such as dynamic programming and GA. In the literature, there are several alignment optimization studies focusing on the 2-D solutions considering either vertical or horizontal planes. Numerous researchers implemented horizontal and vertical alignment models so far [9-23]. The fundamental differences among implemented 2-D depend on the employed optimization technique. In this context, several techniques such as linear programming, quadratic programming, gradient search, state parameterization, and dynamic programming are used for the solution of alignment optimization problem in 2-D manner.

On the other hand, 3-D solution of the problem is also treated by several researchers. Turner and Miles [24] implemented a highway alignment technique calculating the shortest paths on a grid network which is representing relative costs of different alternatives. More complex studies are performed for the solution of highway alignment optimization problem in 3-D manner. Different from 2-D studies, dynamic programming, state parameterization, and genetic algorithm approaches applied to calculate route candidates in 3-D manner [1,2,9,25-27]. Nevertheless, complex behavior of 3-D models, which requires extensive computational effort, make them impractical as well as inefficient in most alignment problems [1,28]. WGLM, primarily focusing on vertical alignment concept, recently suggested to perform optimal alignment analyses practically[7,8]. Besides, WGLM also includes several soil parameters that may affect realistic earthwork calculations. These parameters can be determined by a fuzzy decision support system [7]. It should be noted that WGLM based alignment optimization process was later completed by adding a GA to decide final vertical alignment [8].

WEIGHTED GROUND LINE METHOD

Primarily, vertical alignment is performed due to the centerline of the road; thus, the center line is accepted as the reference line. However, the center ground elevations seldom characterize the topography of a cross section. The term WGE is a hypothetical center elevation characterizing the topography in terms of earthwork optimization, namely cut-fill balance and total earthwork minimization. The mathematical expression of WGE is given by [5]:

(1) $\sum_{i=1}^{n} S_C(i) = \sum_{i=1}^{m} S_F(i) \qquad (for\ y = h_w)$

in which, h_w is WGE, $\mathbf{S_C}$ is cut area vector, $\mathbf{S_F}$ is fill area vector, n is the number of cut areas in cross section, and m is the number of fill areas in cross section. The expression of WGE is as given below:

(2) $h_w = \dfrac{\int_0^L \phi(x)dx + (-S_{CS} + S_{FS})}{L}$

where, $Ø(x)$ is natural surface function, L is earthwork width, S_{CS} is triangular shaped excess area due to cut slope, S_{FS} is triangular shaped absence area due to fill slope. As can be derived from Eq.1, the triangular areas should be subtracted for a cross section in cut, be added for a cross section in fill. It can be derived from Eq.1 that, the earthwork width must be known to calculate h_w; nevertheless, it's not possible to know the earthwork width before the centerline elevation of the road template is fixed. In order to solve this recursion problem, an iterative procedure (Figure 1) is applied progressively until previously determined confidence level (δ) is met [5].

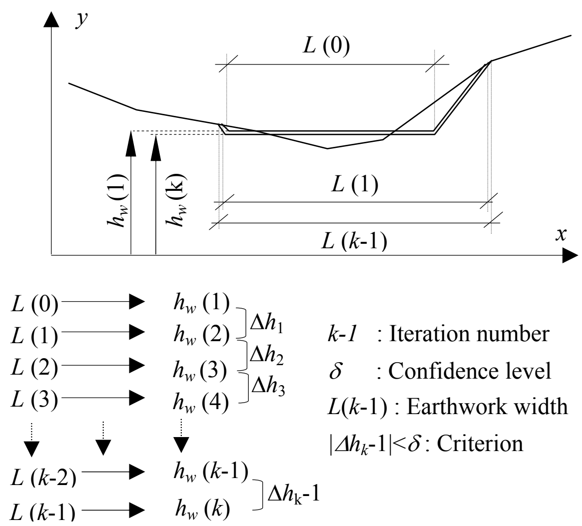

Fig.1. *Iterative procedure for the calculation of earthwork width [5]*

Obviously, there are some soil properties that may affect realistic volume calculations. Namely, excavated material may not occupy the same volume when placed in fill due to shrinkage and swelling attributes. Besides, every cut material is not appropriate for use as a fill material. Therefore, following material properties were included in the method [6]: a) Swelling percent of material after excavation (P_S), appropriateness percent of cut material (P_A), and compactibility percent of fill material (P_C).

The material property, named Appropriateness Percentage (P_A) was presented to consider above mentioned soil properties resulting in volumetric changes. Consequently, Material Parameter (C_M) combining all three parameter is defined as follows [6]:

(3) $C_M = \dfrac{P_A \times (1 + P_S)}{(1 + P_C)}$

The Material Coefficient (C_M) is a refinement parameter correcting calculated cross sectional areas to enhance the precision of earthwork volume calculations. Consequently, the relationship between calculated cut and fill areas is expressed as given below:

(4) $\sum_{i=1}^{m} S_F(i) = C_M \times \sum_{i=1}^{n} S_C(i)$

C_M coefficient is a kind of fine tuning for calculating realistic cut and fill volumes. It should be noted that, if $C_M > 1$, the cut areas cut areas should be decreased, and if $C_M < 1$, then the sum of fill areas should be decreased to have better earthwork balance. Finally, with the definition of ΔH parameter as the distance between h_w and h_w', modified weighted elevation (h_w') can be calculated as given below [6]:

$$\Delta H = \frac{C_1 \times g(\Delta H)}{L(\Delta H)} \qquad (6)$$

$$\begin{aligned} &\textit{where}\ , \\ &C_1 \quad : 1 - C_M \\ &g(\Delta H) : \sum_{i=1}^{v} S_C'(i) \quad \textit{for} \quad y = (h_w - \Delta H) \\ &L(\Delta H) : L' \quad \textit{for} \quad y = (h_w - \Delta H) \end{aligned}$$

(5) $h_w' = h_w - \Delta H$

in which, ΔH the shifting for $y = h_w'$ and h_W' is modified WGE considering material properties. Consequently, following equation is given for the calculation of ΔH shifting [6].
where, S_C' is cut area vector for new positioning, v is the number of new cut areas, and L' denotes the final earthwork width. The value of ΔH can be found by using an iterative root calculation procedure, such as Method of False Position [6].

DETERMINATION OF SOIL PARAMETERS

It is possible to combine swelling and shrinkage attributes in a unique parameter, namely swelling/shrinkage factor, which can be considered by using field densities measured before excavation and after compaction. In this manner, swelling/shrinkage factor can be calculated by utilizing field unit weight and maximum unit weight obtained by Proctor compaction test. Therefore, relative compaction ratio (C_R) can be calculated with the following equation [7]:

(7) $$C_R = \frac{\gamma_{df}}{\gamma_{dmax}}$$

where, γ_{df} is field dry unit weight and γ_{dmax} is the maximum dry unit weight. The parameter C_R is a part of compaction control procedure which is conducted over the construction process. Therefore, relative compaction parameter depends on project specifications and field compaction procedure. Contrarily, C_R parameter considered should be measured before earthwork construction begins. The relationships between swelling/shrinkage factor (F_S) and material coefficient (C_M) are given below [7].

(8) $$F_S = \frac{C_M}{P_A} - 1 = \frac{1 + P_S}{1 + P_C} - 1 = \left(\frac{C_R \times \gamma_{d\max}}{\gamma_{df}} - 1 \right)$$

(9) $$C_M = F_S P_A + 1 = \frac{P_A(1 + P_S)}{1 + P_C} = \frac{P_A C_R \gamma_{d\max}}{\gamma_{df}}$$

Even though F_S parameter can be calculated by Eq.8 directly, it would be better to perform necessary tests before the construction begins. In addition, soil behavior includes certain amount of uncertainty, which making incapable of characterizing them by certain expressions. Besides, need for the determination a representative relative compaction (C_R) value before construction works may result in serious ambiguity; thus, a decision support system can be useful for designers to choose proper values during the design phase. In this context, the existing uncertainty in the model parameters (γ_{df}, γ_{dmax}, C_R, and F_S) was considered by fuzzy logic, and a rule-based system was designed to make needed inference by [7]. Details of the fuzzy logic based decision support system for choosing the model parameters needed for alignment optimization can be found elsewhere [7,8].

Apart from swelling and shrinkage behaviors of fill material, the appropriateness of cut material to properly use as a fill material is described by P_A percent. Basically, the parameter P_A is crucial for specific conditions, such as roads constructed on weak soils or projects constructed on liquefiable soils. The determination of this parameter is also affected by technical specifications, international standards, and individual experiences. Additionally, we usually have geotechnical information about the soil formation before the design stage; thus, it is possible to consider unsuitable soil regions on the route and to characterize the regions for better material hauling. Obviously, the determination of material appropriateness should be made due to the technical specifications or design standards. For example, according to the Technical Specifications of Turkish General Directorate of Highways, California Bearing Ratio (CBR) must be greater than 10% and weak soils (topsoil, marl, peat, etc) cannot be utilized as fill material [29]. Besides, following criteria are determined for the appropriateness of fill materials: (a) $\gamma_{dmax} \geq 1.45 t/m^3$, (b) LL ≤70, (c) PI ≤40, and (d) CBR ≥ 10%.

A method for the consideration of P_A parameter was suggested by Goktepe, et al [7,8]. In this method, satisfaction of above criteria is closely related with soil classification. In Fig.2, a representative unsuitable soil region in a cross section of the roadway is given [7,8]. The definition of P_A parameter characterizing the material suitability is given below:

$$(10) \quad P_A = \frac{S_C - S_U}{S_C}$$

where, S_C is total cut area and S_U is the sum of unsuitable area. Further information on the method can be found elsewhere [8] After the determination of F_S and P_A values for each cross-section, material coefficient (C_M) can be calculated by using Eq.9. Subsequently, modified WGEs can be obtained by applying C_M correction.

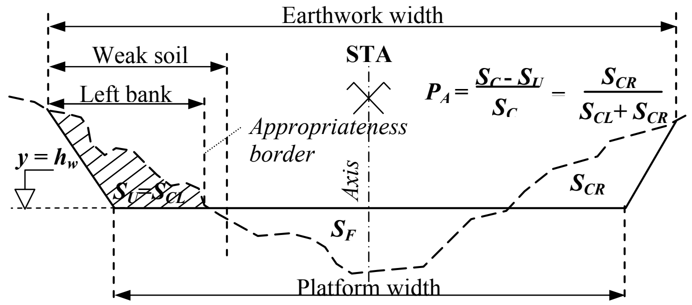

Fig. 2. *Cross section for P_A calculation*

VERTICAL ALIGNMENT WITH GA

GA, which is a heuristic (or direct) searching technique, utilizes the evolution theory on the basis of “survival of the fittest” rule. Referring to its unique searching ability, GA is very popular and successful optimization methodology. GA technique is very successful for nonlinear optimization problems including several local minima, and multi-constraints. In the first step of GA calculations, the solution alternatives are created and the performances are compared with each other. Decision variables are first represented by genes which are characterized by binary strings. Parent solution (or individual) is also referred to as chromosome. In the first step of GA iterations, a number of solution alternatives are generated and their fitness values are compared. It should be noted that the initial parent solution is obtained randomly. Subsequently, new individual (namely offspring) is generated by using previous individuals. There are three fundamental processes in a GA to produce new individuals: (a) reproduction, (b) crossover, and (c) mutation. The reproduction is based on a stopping creation and testing of different possible solution alternatives due to the fitness function’s value. It should be added for crossover process that the good solution is selected from the alternatives, and remained choices are excluded. Consequently, new individuals are produced by the mutation process [3,8,30-32]. The schematical representation of GA approach is given in Figure 3.

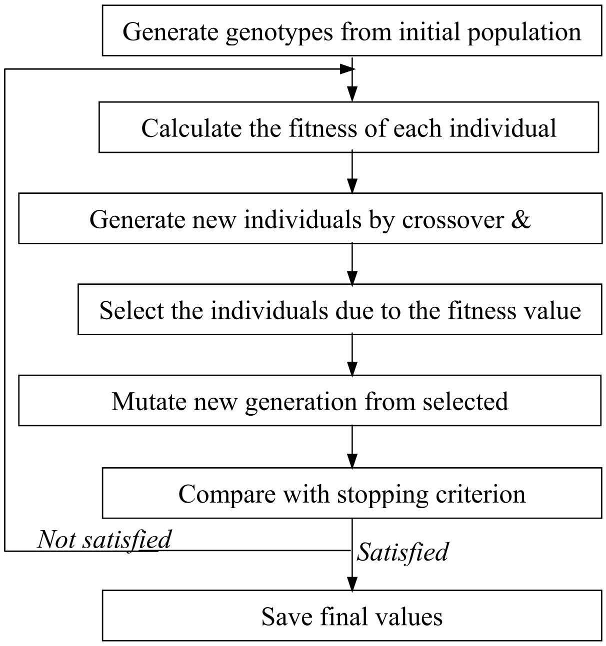

Fig. 3. *Flow chart of the GA*

Let's assume WGL and grade line are denoted by y_i and f_i, respectively. Besides, t is the number of stations (STAs), d is the number of conjunction points (vertical curve points), $w(i, 1)$ is x coordinate of WGE matrix, $w(i, 2)$ is y coordinate of WGE matrix, $f(i, 1)$ is x coordinate of grade line matrix, $f(i, 2)$ is y coordinate of WGE matrix, $I(j, 1)$ is x coordinate of intersection matrix, $I(j, 2)$ is y coordinate of intersection matrix, and m_i represents the slope of the tangent line. Obviously, final vertical alignment is the combination of d+1 straight lines connected to each other at intersection points. In this context, the role of GA is to find out the conjunction points using its unique heuristic searching ability. Under the light of this philosophy, following piecewise expression can be used to calculate new grade elevations [8,33]:

(12)
$$\Bigg|_{i=1}^{t-1} \Bigg|_{j=1}^{d} \begin{array}{l} \text{IF } I(j-1,1) \le f(i,1) \le I(j,1) \Rightarrow \\ \quad f(i,2) = I(j-1,2) + m(j)\big(f(i,1) - I(j-1,1)\big) \end{array}$$

On the other hand, the fitness function required for GA-based vertical alignment optimization model can be based on the minimization of sum of squared differences between calculated WGEs and grade elevations. Therefore, the fitness function (R) can be written for tangent sections as follows [8]:

(13)
$$\min(R) = \min\left(\sqrt{ \sum_{i=1}^{t} \left\{ w(i,2) - \left(\begin{array}{l} I(j-1,2) + \\ \left[f(i,1) - I(j-1,1) \right] \times \\ \dfrac{I(j,2) - I(j-1,2)}{I(j,1) - I(j-1,1)} \end{array} \right) \right\}^2 } \right)$$

Finally, the fitness

s function (R) can be modified for a STA on a vertical curve as given below [8]:

(14) $$\min(R)=\min\left(\sqrt{\sum_{i=1}^{t}\left\{w(i,2)-\begin{pmatrix}I(j-1,2)+\\ \dfrac{m(j-1)-m(j)}{2Lv}\times\\ \left(f(i,1)-I(j-1,1)\right)^2\end{pmatrix}\right\}^2}\right)$$

in which, Lv is the length of vertical curve and R represents the fitness function based error value to be minimized. Furthermore, design constraints can be considered in GA model accordance with AASHTO 2001 design specifications. Further information on design constraints and their consideration in the alignment model can be found elsewhere [8,33].

CONCLUSIONS

The aim of this study is to present WGLM for vertical alignment of highways. The method also considers soil parameters, i.e. swelling/shrinkage factor and appropriateness percent. Furthermore, previously implemented fuzzy logic based decision support system for soil parameter selection and GA supported vertical alignment method are also presented. Consideration of related soil parameters in the highway alignment process enables us to increase the precision as well as to handle heterogeneous, ambiguous, and mixed soil parameters in this respect.

Any of presented techniques can also be utilized in any highway design process separately. Namely, WGLM or fuzzy inference system or GA based vertical alignment procedure can be used in any highway design alone.

Presented alignment optimization procedure may result in serious economic and environmental advantages for highway projects.

The fitness function included in the GA based optimization model only considers the earthwork costs; however, there are different factors, such as pavement, environmental aspects, and right-of-way costs, affect the alignment optimization process. The fitness function can be modified for including such factors to get more comprehensive alignment results. This issue can be topic of another study.

The method is not only for highway projects, but also applicable to other civil engineering projects, such as railways, open canals, etc., comprising a platform constitution with earthwork operations.

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ОПТИМАЛНО ПОДРАВНЯВАНЕ НА МАГИСТРАЛИ НА ОСНОВАТА НА ПРЕТЕГЛЕНА ЗЕМНА ЛИНИЯ

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Ключови думи: *земни работи, подравняване на магистрала, оптимизация, претеглена земна линия, размита логика, генетичен алгоритъм*

Анотация: *Оптимизирането на земните работи е от особено значение в процеса на проектиране на магистрала в икономически и времеви аспект. В този контекст за оптимално подравняване трябва да се вземае предвид балансът на изкопите и насипите, както и цялостното минимизиране на земните работи за намаляване на разходите за земните работи. В съществуващата практика сега обичайният начин да се оптимизира размера на земните работи е да се установи линията на наклона възможно най-близо до земната линия. Въпреки това този подход може да бъде подвеждащ, тъй като земната линия на пътя, която се формира от централната линия, не може да се характеризира топографията на напречното сечение. Следователно централната кота не може да представлява цялото сечение по отношение на балансирането на изкопите и насипите и цялостно минимизиране на земните работи. Това е един голям недостатък особено за проекти, разположени в планински терени.*

Weighted Memod Ground Line Method (WGLM) е техника за оптимизиране на подравняването в зависимост от хипотетична референтна линия и съобразяването с три основни свойства на почвата, а именно потенциала за подуване, процента на компактност и процента на на избор на подходящ материал. Трябва да се отбележи, че не всичкият материал от изкопите може да се използва като запълващ материал в резултат на несъответствие между обема на изкопите и обема на запълване след уплътняването. В допълнение изкопаният материал може да не е подходащ за използване като запълващ. Тези атрибути на почвата са нзети под внимание от метода WGLM с различни параметри, за да се постигне реалистична оптимизация на земните работи по отношение на балансирането на изкопите и насипите и общо минимизиране на земните работи.

Резултатите показват, че методът, основан на WGLM, на система, базирана на размита логика и еволюционно изчисляване води до изключителна способност за намиране на подходяща крива за геометричен дизайн на магистрали. Методът може да се използва също и за решаване на други проблеми по отношение на подравняването в строителството като например железопътни линии, открити канали и др.