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Horizontal Corridor Optimization of Highway Using GIS Considering Retaining Wall Costs in Mountainous Areas

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ABSTRACT

Defining the optimal horizontal corridor of a highway through an area is one of the major decisions in road design to minimize total cost. It is considered one of the most complicated spatial problems which can hardly be solved without using Geographic Information Systems (GISs), because of its significant property of controlling a large amount of spatial and non-spatial data, in addition to performing many types of analysis.

Some of the construction costs is related to the highway profile, such as the roadside retaining walls. The need for retaining walls should be recognized during the preliminary design phase and should be shown on the hearing plan (NHDOT, 2014).

This study aims to estimate the retaining wall effect in determining the optimal horizontal corridor of a highway at the preliminary design phase. The locations and heights of predicted retaining walls are determined with the application of GIS by using the Least-Cost Path Analysis (LCPA) method. On the other hand, the Circular Failure Chart (CFC) method is incorporated to evaluate the safe height of the slope. A mathematical model for finding the optimum corridor between two points is implemented, considering the impact of retaining wall costs.

KEYWORDS: Optimum horizontal corridor, Construction costs, Road planning, Retaining walls, Slope stability.

INTRODUCTION

Optimizing horizontal alignment models is more complex and usually needs more spatial and non-spatial data compared to that required for profile optimization (OECD, 1973). Costs related to horizontal alignment of a highway are considerably affected by its profile. However, cost reductions due to horizontal alignment optimization are considerably higher due to high land use cost, construction cost, social and environmental costs (ASTM, 2013).

Effat, H. A. et al. (2013) and Obaidat et al. (2018) concluded that GIS provides a valued tool in the process of planning highways. GIS tools help create, query, analyze and map cell-based raster data and perform integrated vector-raster analysis using feature- based and grid-based layers. Embedding GIS and shortest path algorithms in the early planning system is well-suited, economical and time-saving for a sustainable corridor location design. HIRPA (2014) showed that using GIS or other network optimization approaches makes finding the optimal horizontal corridor essential before finding the optimal horizontal alignment. This step usually helps overcome many deficiencies; for example, the outputs being not smooth or the LCPA approach in GIS being not suitable for continuous search in space.

Studying the retaining wall effect needs an

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alignment's profile data to have information regarding the cut height and related soil layer types. In this research, we suggest a method to predict the retaining wall locations and heights using the available data, like CBR, as well as geological and topographic maps. Thus, we can estimate the preliminary retaining walls' costs and their effect on finding the optimal horizontal corridor without having the profile data. The study of the corridor path between the cities of Latakia and Slunfeh in Syria was adopted as an application for this research.

MATERIALS AND METHODS

Highway Cost Items

Numerous studies have classified highway cost items (Winfrey, 1968; Moavenzadeh et al.,1973; OECD, 1973; Watanatada et al., 1987; Wright, 1996; Jong, 1998; Jha et al., 2001; Son et al., 2002). According to these studies, it is noticed that there is no consensus on cost classification of highway alignment. Table (1) shows the most used classification of highway cost items with their sensitivities in recent related papers. The table also shows the high sensitivity of structure costs according to (Son et al. (2002).

Table 1. Classification of highway costs

Main specification	Sub-specification	Cost items	Sensitivity to alignment
Supplier costs	Administrative costs	Planning, consulting and supervision costs	Low
	Construction costs	Earthwork costs	High
		Right-of-way costs	High
		Pavement costs	High
		Hydrology (drainage) costs	Low
		Guardrails and lighting costs	Low
	Maintenance costs	Pavement re-gravel costs	Low
		Roadside mowing costs	Low
		Guardrails and lighting maintenance costs	Low
	Structure costs	Intersections	High
		Bridges and tunnels	High
		Interchanges	High
		Overpass and underpass	High
User costs	Travel time costs	Vehicle miles traveled (VMT)	High
	Accident costs	Estimated accident rates	High
	Vehicle operating costs	Fuel, tire wear and depreciation of vehicles	High
	Environmental costs	Noise costs	Medium
		Air pollution costs	Medium
		Impacts of environmentally and socially sensitive objects	High

According to Kang et al. (2012), structure and earthwork costs may dominate if a highway is constructed in a mountainous area. As per the studies mentioned earlier, the construction cost of free-standing retaining walls was not considered.

Study Area and Data Used

The study area was selected in the Mediterranean Sea region of Syria. The origin point is Latakia city (next to the sea) and the destination point is Slunfeh town (in the mountainous part), as shown in Figure (1). Route length is approximately 70 km.

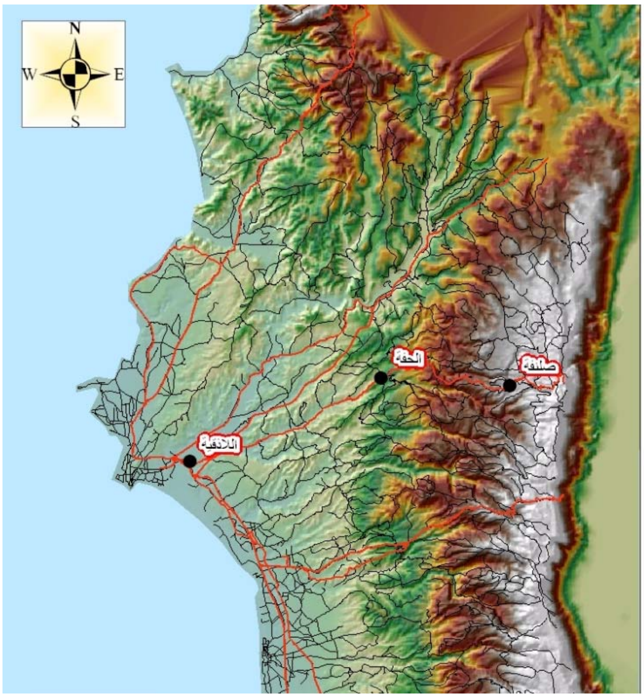


Figure (1): Map of region of study in Latakia city

GIS maps used in corridor optimization contain the most sensitive costs related to supplier costs only, as shown in Table (2).

The studied area was divided into a group of cells with appropriate dimensions of (400x400) m according to the scale of the available data and required width of horizontal corridor. The cost was calculated for each cell, according to Khalil (2010). It included the most sensitive costs from a similar highway project (Ariha-Latakia highway), located in the same study area.

Table 2. Data used in the optimization of highway horizontal corridor

Data layers	Attributes	Data source	Scale
Elevation	Slope	General Organization of Remote Sensing	1/250000
Land use	land use, irrigated lands	General Organization of Remote Sensing	1/100000
Geology	Soil types, CBR	General Establishment of Geology & Mineral Resources	1/100000
Stream	Name, flow	Directorate of Technical Services in Latakia	1/100000
Road	Name, type, class	General Organization of Road Transport in Latakia	1/100000

The costs of roadside retaining walls are related to cut height and soil types. Slopes are classified as shown in Figure (2). It is assumed that the cut height will equal zero if the slope of existing land is equal to the maximum allowable grade ±10%.

California Bearing Ratio (CBR) is usually used in road projects. Due to lack of geotechnical design factors; namely, cohesion, friction angle and dry density, it was decided to extract them from the CBR data of Ariha-Latakia highway. Figure (3) shows the soil types according to the available geological soil map in the study area.

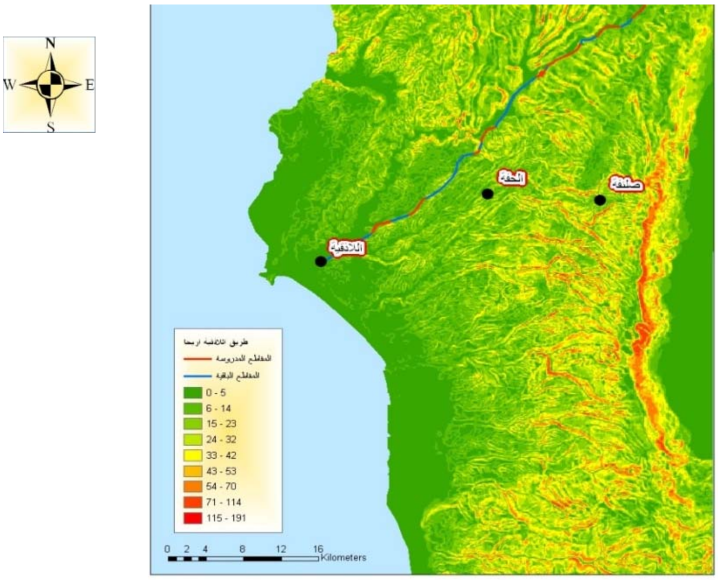


Figure (2): Slope classification

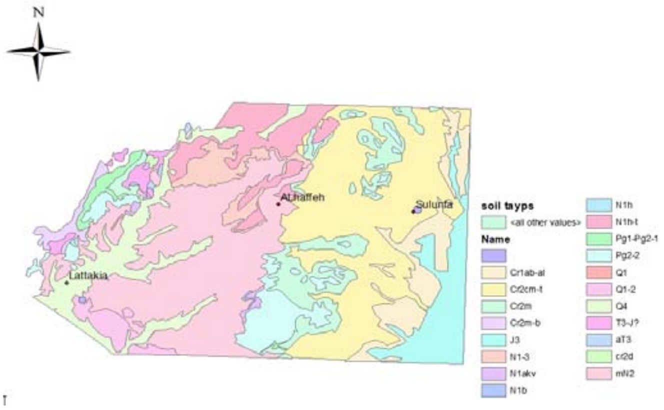
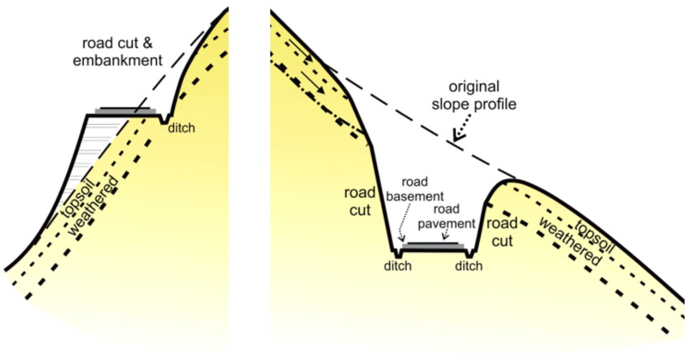


Figure (3): Soil types according to geological soil map

In mountainous areas, a flat horizontal area has to be made to allow a flat road to be constructed as per (AASHTO, 2003). To avoid too steep gradients, roads may have to be routed alternatively over a flatter, less hilly and mountainous terrain, made through a "cut" in a hill or a mountain, as shown in Figure (4). The case of road cut will be discussed in this paper.



(a) (b)

Figures (4): Roadside retaining walls in a mountainous terrain:
(a) road cut and embankment; (b) road cuts

Effect of Slope Stability and Related Necessity of Retaining Walls

According to the available CBR values, geotechnical properties, such as cohesion (C), friction angle (φ) and density (γ), can be estimated for the slopes at road sides, which play an important role in retaining wall design. For this purpose, the following equations are used according to the experimental studies carried out by Yashas et al. (2016):

$$\gamma = 1.288 *(CBR)\ 0.1324$$
$$C = 0.052* (CBR)\ 0.675$$
$$\phi = 39.956-0.204*(CBR)$$

After estimating the soil properties, the circular failure chart (CFC) method is incorporated to evaluate the safe height of a slope, consequently evaluating the requirements of supporting systems, such as a concrete retaining wall. The (CFC) method facilitates a quick and easy way to calculate and understand the slope factor of safety, according to Hoek and Bray (1981). It is worth noting that this method can be used with varying groundwater conditions, but it is still constrained to the following assumptions:

- The material forming the slope is assumed to be homogeneous and fully drained;
- The shear strength of the material is characterized by a cohesion (C) and a friction angle (ϕ) which are related by Equation (1):

$$\tau = C + \tan(\phi); \qquad (1)$$

- Failure is assumed to occur on a circular failure surface, which passes through the slope's toe;
- The factor of safety of the slope is defined as:

$$F = \frac{\text{shear strength available to resist sliding}}{\text{shear strength mobilized along failure surface}}$$

Rearranging this equation, we get Equation (2):

$$\tau_{mb} = C/F + \sigma*\tan\Phi/F; \qquad (2)$$

where τ_{mb} is the shear stress mobilized along the failure surface.

Figure (5) shows the circular failure chart for dry condition used to deduct the safe height of the cut slope.

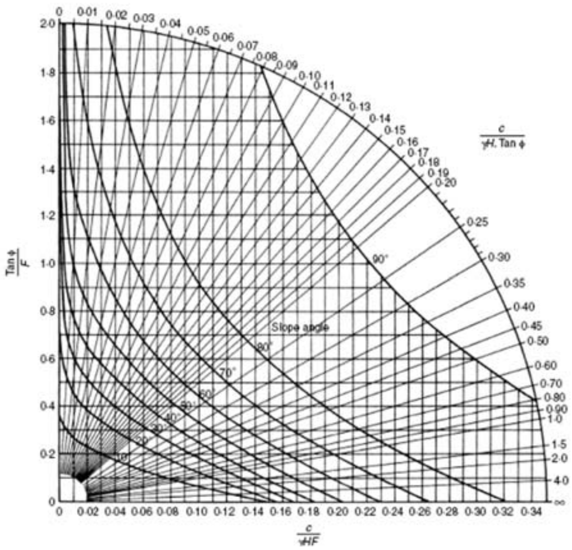


Figure (5): Circular failure chart according to Hoek and Bray (1981)

The CBR values are grouped into four main categories. Figure (6) shows the relation between CBR and slopes in the study area.

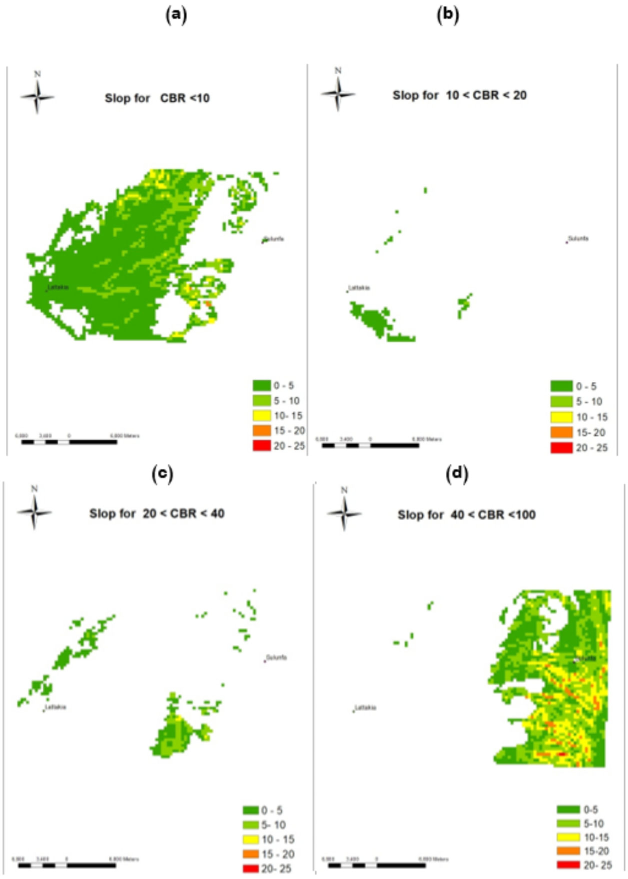


Figure (6): The relation between CBR and slopes:
(a) slope for CBR <10; (b) slope for 10< CBR <20;
(c) slope for 20< CBR <40; (d) slope for 40< CBR <100

RESULTS AND DISCUSSION

Table (3) summarizes the averaged soil properties calculated according to CBR values and the resulting safe height of a cut slope deduced from the circular failure chart.

Table 3. Averaged soil properties calculated according to CBR values

CBR	Friction angle Φ°	Cohesion C (kN/m^2)	Density γ (kN/m^3)	Safe height H (m)
>10	38.2	23	17.2	3
11 - 20	37.31	30.66	18.2	3.5
21 - 40	32.89	58.5	20.7	5
> 40	19.63	119	23.8	8.5

The safe height of a cut slope shown in Table (3) is then used as a criterion for evaluating the requirements of a retaining wall.

Consequently, for each CBR category, we can estimate the cost of the expected retaining wall in correlation with the natural slope angle. The assumed retaining wall length will equal a cell size. At the same time, average heights are calculated according to highway width (20m) and slope angle, taking into consideration the allowable vertical cut slope for each category of CBR, as shown in Table (4). Reinforced concrete retaining walls are adopted during cost estimation and the costs are extracted according to prices in 2010 (1$ = 50 S.P.).

Table 4. Expected average height of excavation with related costs

CBR	Slope angle (degree)	Expected average height of excavation (m)	Cost in Syrian Pounds (S.P.)
>10	0-10°	≤3	0
	10°-15°	3.5	112 000 000.00
	15°-25°	9	160 000 000.00
	25°-30°	11.5	272 000 000.00
	30°-45°	20	320 000 000.00
	≥45°	no data	no data
11 to 20	0-10°	0	0
	10°-15°	0	0
	15°-25°	9	160 000 000.00
	25°-30°	11.5	272 000 000.00
	30°-45°	20	320 000 000.00
	≥45°	no data	no data
21 to 40	0-10°	0	0
	10°-15°	0	0
	15°-25°	0	0
	25°-30°	11.5	272 000 000.00
	30°-45°	20	320 000 000.00
	≥45°	no data	no data
40 to 100	0-10°	0	0
	10°-15°	0	0
	15°-25°	0	0
	25°-30°	0	0
	30°-45°	20	320 000 000.00
	≥45°	no data	no data

As per Figure (6), the maximum slope in the studied area is 25°. Accordingly, there are only two classes of retaining walls, as shown in Figure (7).

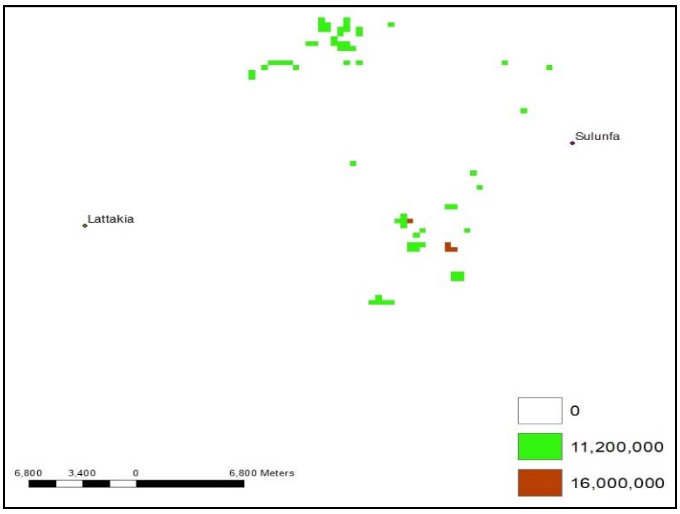


Figure (7): Existing retaining wall cells with related costs (S.P.)

The final accumulative cost raster for all studied factors, including the retaining walls, is shown in Figure (8).

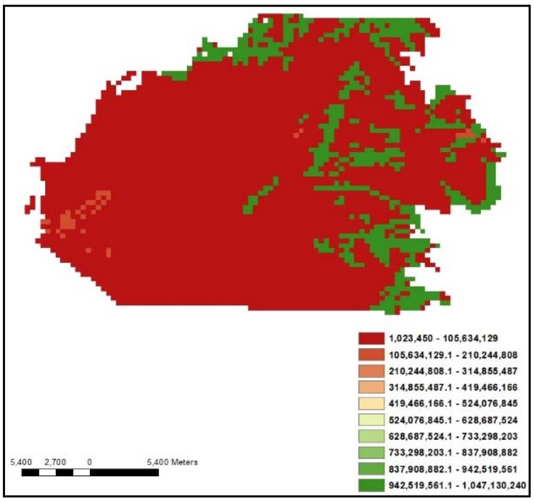


Figure (8): Accumulative cost matrix (S.P.)

Figure (9) shows the impact of retaining wall costs on extracting the highway's horizontal corridor during the preliminary design stage. Red points show the deviation of the horizontal corridor due to retaining wall costs in the cut area.

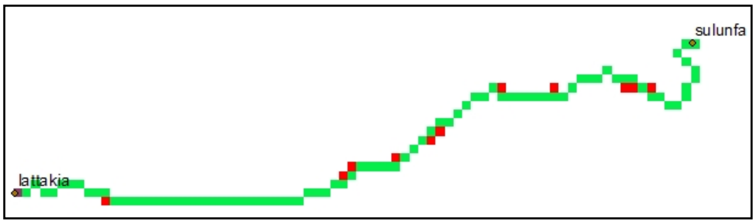


Figure (9): Deviation of the horizontal corridor due to retaining wall requirements in the cut area

The total cost of road construction at the preliminary design stage after taking retaining wall costs into account amounts to 1,164,267,621 S.P. (23,285,325 $), but the total cost without taking retaining wall costs into account is 1,143,640,371 S.P. (22,872,807 $). Accordingly, the cost difference is about 1%. In a similar study, other structure costs are about 15% of the total cost.

Figure (10) illustrates the different steps for including the cost of supporting retaining walls in GIS methodology for choosing the optimal horizontal corridors of highways.

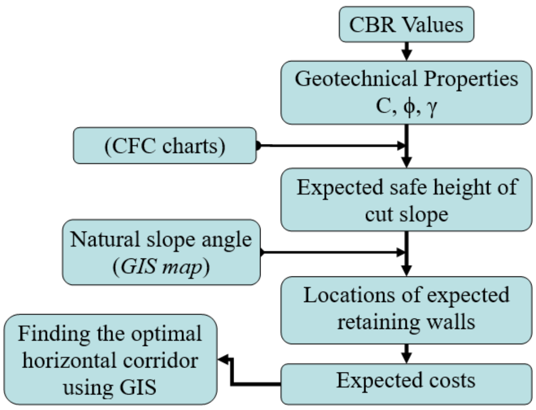


Figure (10): Flowchart of using retaining wall costs in extracting the horizontal road corridor using GIS

CONCLUSIONS

Structure costs may dominate if a highway is constructed in a mountainous area. As per the studies of cost classification of highway alignment, it is noticed that the construction cost of free-standing retaining walls was not considered. For that reason, the effect of free-standing retaining walls was analyzed and a procedure to include it as a cost parameter at the preliminary design stage of horizontal highway corridors was proposed. The findings in this research led to the following conclusions:

1. GIS applications are powerful tools that help highway engineers and stakeholders in extracting the highway optimal horizontal corridor, especially at the preliminary design stage.
2. Free-standing retaining wall cost is about 6.7% of other structure costs.
3. Free-standing retaining wall cost is about 1% of the total cost. According to the adopted cost classification in Table (1), retaining wall costs can be classified as low.

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