ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25mar1138

Road Alignment Optimization in Landslide-Prone Areas: A GIS-Based Approach in Yatiyanthota, Sri Lanka

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Publication Date: 2025/04/01

Abstract: This study focuses on road alignment optimization in a hilly region of Sri Lanka, specifically the Yatiyanthota and Yatiyanthota town areas, which are prone to landslides. This research aims to use GIS techniques to optimize the road alignment design for a proposed bypass road in the area, taking into account economic, environmental, and societal factors. Traditionally, engineers have used manual drafting techniques to design road alignments, but this method has limitations, particularly in considering multiple spatial factors simultaneously. Therefore, GIS techniques, such as the Least Cost Path algorithm in ESRI's ArcGIS, are used to generate optimal alignment alternatives for the bypass road. The study compares and assesses the optimal alignment alternatives in order to bypass landslide-prone areas in Yatiyanthota, which was considered several factors simultaneously. The results show that the least cost optimal alignment coincides with the engineering factors than all other assessment criteria. Additionally, the optimal alignment is shorter, and the cut/fill cost is reduced compared to the existing alignment. This research provides valuable insights into using GIS techniques to optimize road alignment design in hilly regions with complex geography and geology prone to landslides and earthquakes, with implications for road development projects in Sri Lanka and other similar regions.

Keywords*: Remote Sensing, Geographic Information System, Optimization Techniques, Least Cost Path Analysis, Multi Criteria Decision Making.*

How to Cite: G.D.V.C Dissanayaka; T.D.C. Pushpakumara (2025) Road Alignment Optimization in Landslide-Prone Areas: A GIS-Based Approach in Yatiyanthota, Sri Lanka. *International Journal of Innovative Science and Research Technology*, 10(3), 1713-1719. https://doi.org/10.38124/ijisrt/25mar1138

I. INTRODUCTION

Roads play a crucial role in a country's economic and social development. In Sri Lanka, the development of the transportation sector is of great importance to connect rural areas with urban centers, enhance tourism, and create job opportunities. Yatiyanthota is a hilly region in Sri Lanka that suffers from natural disasters such as landslides, floods, and soil erosion, which makes transportation through the area challenging. The Colombo Hatton highway that passes through Yatiyanthota is a popular tourist route in Sri Lanka, and the existing road faces frequent landslides and heavy traffic congestion during peak seasons (Yatiyanthota Divisional Secretariat, 2018).

The Colombo-Hatton Main A-type road is a major transportation route that passes through the town of Yatiyanthota in Sri Lanka. It is a significant road that links Sri Lanka's central regions with the rest of the country. The road passes through a mountainous region with steep slopes, which makes it vulnerable to landslides, especially during the rainy season (Gamage & Karunananda, 2016). Yatiyanthota town has experienced several landslides in the past. In 2017, a major landslide occurred in the area, which resulted in several fatalities and caused significant damage to property and infrastructure. This event highlighted the need for effective measures to manage the landslide susceptibility of the area.

Therefore, there is an urgent need to identify optimized road alignments to the existing route in this region to ensure safe and efficient transportation for the residents and visitors. GIS is an effective tool for road alignment optimization as it can simultaneously analyze and simulate several factors (Li & Li, 2012). By considering several criteria, such as cost, safety, and environmental impact, GIS can help identify the optimal road alignment that minimizes the negative effects of natural disasters and enhances connectivity.

This research aims to use GIS techniques to optimize the road alignment in the landslide-prone area near Yatiyanthota town, which is part of the Colombo Hatton highway. The research will consider several factors, including environmental and socio-economic impacts, and

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25mar1138

propose a new route that will be more efficient and safer than the existing one.

➢ *Research Objectives*

The research objectives aim to address road alignment optimization in the hilly region of Sri Lanka using GIS techniques, specifically focusing on:

- Identifying specific impact groups, criteria, and factors relevant to the study area.
- Generating optimal alignments respective to Engineering, Environmental, Economic, Social, Transport and additional alignment generated by combining the above-mentioned impact groups.
- Evaluating the total impact groups and finding the optimum alignment using GIS tools and CAD basis techniques.

II. LITERATURE REVIEW

A developing country like Sri Lanka seeks the most economical roadway types to improve its deficit of transportation requirements. Proposing roadway alignment for a hilly landslide susceptibility area of Sri Lanka is challenging due to its complex geography, geology, and vulnerability to landslides (Link, 2020a). Landslides can cause economic and physical damage to road networks (Donnini et al., 2017). In Sri Lanka, road terrains mainly located in the hilly areas are frequently subjected to landslides, increasing maintenance costs and causing heavy traffic due to road closures (Padmani & Sudath, 2016).

Economic and urban development of small cities leads to traffic congestion, safety issues, noise, and air pollution. Bypass roads have been introduced to overcome these cons, with the main objective of mitigating traffic congestion while increasing mobility. Transport and urban planning agencies should perceive the potential physical and socio-economic impacts of their proposals, especially in towns located in hilly areas where challenges are greater and many variables must be considered (Sewwandi & Jayasinghe, 2021).

The traditional highway design process requires experienced engineers, enormous time, and tools to determine the best alternative (Awwad, 2005). The following drawbacks were identified in the study by Yakar and Celik (2014):

- Essential criteria such as environmental, economic, social, and traffic techniques could not be considered during the alignment proposing stage.
- The proposed alignment could not be optimum; consequently, criteria cannot be handled simultaneously.
- Environment and society could not be considered sufficiently.
- Inadequate proposed structure data at the planning stage might lead to structures like bridges and retaining walls being needed during the construction phase, resulting in more costs.

Many studies were conducted related to "Highway alignment optimization" using different methods. In single objective studies, the principal objective is minimizing the cost (Link, 2020a). The proposed alignment should also satisfy engineering design standards such as curvature, gradient, and sight distance (Jha & Schonfeld, 2000).

GIS is a widely used technique in optimization riddles of spatially distributed linear objects such as railways, roads, and highway engineering. Using GIS, spatial variables such as environmental, topography, built-up areas, land use/land cover, and geology-related variables can be easily modeled (Mackenzie & Cusworth, 2007). Analyzing and understanding various parameters for planning and designing the alignment of transport communication has become more accessible due to the ability to consider many spatial variables simultaneously (Van Loon, Rietveld, & Brons, 2011).

The Least Cost Path (LCP) algorithm is an efficacious tool in GIS to determine the optimum roadway alignment (Lee & Stucky, 1998). Cost surface is created using the least-cost path tool, and there are many past studies regarding the algorithm (Awwad, 2005; Bailey, 2003; Subramani et al., 2014; Yakar & Celik, 2014). The LCP tool algorithm slightly depends on the type of software used. The study by Yakar and Celik (2014) uses IDRISI software to simulate the least cost path, and the study by Link (2020a) uses ArcMap to proceed with the optimization.

Multiple methods are used to define weights for different criteria. The study by Yakar and Celik (2014) uses Multi-criteria decision-making (MCDM) and GIS to determine highway alignment. Fuzzy functions were used to standardize criteria maps, and Analytic Hierarchy Process (AHP) was used to determine criteria weights. The weighted linear combination method was used for the combination of criteria maps.

The study by Link (2020a) developed Yakar and Celik's (2014) work by extending the least cost path algorithm to control the slope of the optimized alignment by restricting the vertical cost factor. ArcGIS path distance tool was used to control the slope. A case study was done, and seven alternative alignments were generated using the least-cost path algorithm. Finally, the length of the alignment, geometric feasibility, and cut/fill of the alignment were assessed using a CAD system.

III. METHODOLOGY

➢ *Software and Hardware Tools*

ArcGIS 10.8.1 was the major GIS-based software used for the study, with most of the analysis proceeding on this platform. The Spatial Analysis extension was needed, including the Least Cost Path tool (Link, 2020a). Additionally, Civil 3D and AutoCAD software were used for horizontal and vertical alignment design and cut and fill volume calculations (Abdul, Hadi, & Alhaydary, 2018). Differential global positioning machines were also used for field surveying and verification purposes (Specht, 2023).

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- *Data*

The spatial data used in the research study included building footprints, rivers/drains, land use land cover, road network, origin/destination points, landslide hazard zones, and tourist sites. All data types were clipped or masked to reduce data sizes and processing time. Except for the Digital Elevation Model (DEM), all other data types were in vector format. The raster data and proceeded data were resampled into a 30-meter resolution size.

- *Approach*

The methodology involved composing a GIS-based road alignment optimization method and comparing road alignments designed using traditional approaches with those designed and optimized using the GIS-based method. The approach was primarily based on the works of Awwad (2005) and Yakar & Celik (2014) but contextualized to conform to hilly regions by using additional data, extending the methodology by incorporating constraints on the grade of the road alignment in the optimization process, and using engineering CAD systems like Civil 3D to assess the cut/fill volume and cost realistically.

The GIS-based optimization of road alignment was performed between two obligatory points, origin, and destination, using various spatial criteria to generate six alternative road alignments. The optimal alignment was found using the Least Cost Path Analysis (LCPA) method and then drawn inside an engineering CAD environment to calculate the cut/fill volume and check the geometric feasibility of the alignments based on road design standards.

- *GIS-Based Road Alignment Optimization*

GIS road alignment optimization aims to generate the optimal alignment of a road network that can minimize construction costs and maximize social and environmental benefits (Bhatta, 2010; Padmanabhan & Sudhath, 2016). The LCPA tool is a geoprocessing tool that helps determine the least cost path or route between two points on a cost surface map. Cost surface maps are created using criteria such as topography, land use, soil type, and other factors that affect the construction of roads.

- *Least Cost Path Algorithm (LCPA)*

The LCPA algorithm calculates the least cost path by minimizing the cumulative cost of traversing through each cell, starting from the origin and ending at the destination. The LCPA tool has several stages, including creating the cost surface map, identifying the source and destination points, and calculating the least cost path.

The algorithm is based on Dijkstra's well-known shortest-path algorithm. In the LCPA algorithm, the cost surface map is converted into a graph, where each cell in the raster grid represents a node, and the cost of traversing between adjacent cells represents the weight of the edge connecting the nodes. The LCPA algorithm calculates the cumulative cost of traversing through each cell, and the least cost path is determined by selecting the path with the lowest cumulative cost.

- *Multi-Criteria Decision Making (MCDM) and Analytical Hierarchy Process (AHP)*

MCDM techniques are widely used in GIS-based platforms to solve complex decision-making problems involving multiple criteria. These techniques integrate multiple criteria or attributes in decision-making, allowing decision-makers to evaluate alternatives based on their relative importance.

The AHP is one of the most widely used MCDM methods that helps decision-makers evaluate and prioritize alternatives based on a hierarchical structure of criteria and sub-criteria. AHP involves pairwise comparisons of the criteria and alternatives to derive priority weights, and a consistency ratio is calculated to ensure the consistency of the decision-making process.

The weighted linear combination method is used to combine all criteria maps into a cost surface, as shown in Equation 1:

Equation 1: Weighted Linear Combination Formula

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$$\text{Output Cost} = (w_1 \times cost_1) + (w_2 \times cost_2) + ... + (w_n \times cost_n)$$

Where w represents the weight assigned to each criterion map and cost represents the cost surface map for each criterion.

- *Criteria Identification*

Various parties and stakeholders may have different viewpoints and priorities in road construction projects. This study used five criteria groups (CG) to generate five optimal paths

The weighted linear combination method was used to combine all criteria groups into a single viewpoint. This method involves assigning weights to each criteria group based on expert preferences and opinions. The cost approach was used to conceptualize the criteria, with favourable areas assigned lower costs and unfavourable areas assigned higher costs.

Another least cost path, AHP, is generated by combining all the Criteria Group maps using the Weighted Linear Combination (WLC) method to create a composite cost raster using Equation 2:

Equation 2: AHP Criteria Group Combination Formula

$$AHP = (A \times 0.33) + (B \times 0.15) + (C \times 0.22) + (D \times 0.19) + (E \times 0.13)$$

Where A, B, C, D, and E represent the five criteria groups with weights determined according to expert consultation.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25mar1138

➢ *CAD Analysis*

The six road alignments produced were subjected to a process of conforming to engineering design standards, assessing geometric feasibility, and calculating precise cut and fill volume. The design standards for this road align with the Geometric Design Standards of the Road Development Authority (RDA) in Sri Lanka.

The road template is the cross-sectional geometry of the designed road, with a carriageway width of 9m and shoulder width of 2m. The shoulder on the cut side of the road includes a ditch with a width of 0.6 meters and a remaining width of 0.9 meters.

The least cost paths were adjusted to conform to the RDA design road template, resulting in alignment alternatives that comply with the horizontal curve design standard. Once the vertical alignment was designed and optimized, the cut and fill volume of all the road alignment corridors were calculated.

IV. RESULTS AND DISCUSSION

➢ *Comparison based on Total Cost*

The analysis identified six optimal alignment alternatives to bypass the Yatiyanthota landslide area. These alternatives were assessed based on various criteria, and an assessment table was produced to assist decision-makers in comparing the alignments and selecting the most preferred one. The assessment results are shown in Table 3:

Table 1: Assessment of Road Alignment Alternatives

		Criteria							Total Cost
		Engineering	Economical	Transportation	Social	Environmental	Length	Cut and Fill	
	Weights	0.2	0.1	0.03	0.02	0.05	0.25	0.35	1
Alignment	Engineering	80.53	79.02	93.66	100	86.79	88.5	30.12	65.8243
	Economical	49.53	35.43	53.31	64.3	47.44	94.52	87.39	72.9228
	Transportation	51.33	59.61	33.33	79.37	55.94	90.88	100	79.3313
	Social	100	100	100	62.33	100	100	52.83	82.7371
	Environmental	66.58	64.08	71.94	68.07	65.64	88.66	74.78	74.8636
	AHP	71.33	68.85	74.86	80.2	73.48	89.51	42.81	66.0358

The assessment results showed that the Engineering alignment is the best option, with the Social and Transportation alignments having higher total costs. The Social alignment had the highest cost among the alternatives, almost 30% higher than the least expensive alignment (Engineering).

It is important to note that the assessment should not only consider the total weighted cost but also take into account other factors such as the alignment's performance in other assessment criteria, its length, and the cut/fill costs. The cut/fill cost and the length of the road are particularly significant when selecting the best alignment. The Engineering alignment, which had the least total weighted cost, was also ranked highest in terms of the cut/fill cost (having the least cut/fill cost) and was the shortest alignment. Consequently, it was determined to be the best alignment alternative, with little chance of variation in its rank when assessment weights were altered.

The AHP alignment can be identified as the second-best alternative based on the total cost and cut-and-fill cost perspective. However, the AHP alignment is longer than the Environmental alignment.

The decision between the Economic and Environmental alignments for the third best option is currently undecided. The Economic alignment has a total cost of 72.92, while the Environmental alignment has a slightly higher cost of 74.86, with a negligible difference between them. However, the Economic alignment has a cut/fill cost value of 87.39, whereas the Environmental alignment has a lower value of 74.78. Additionally, the Environmental alignment is very little longer by approximately 0.16 kilometers. Ultimately, the choice between these alignments will depend on the priorities of the decision-makers and industrial experts, whether they place more importance on minimizing cut/fill costs or prioritizing a shorter length for the alignment.

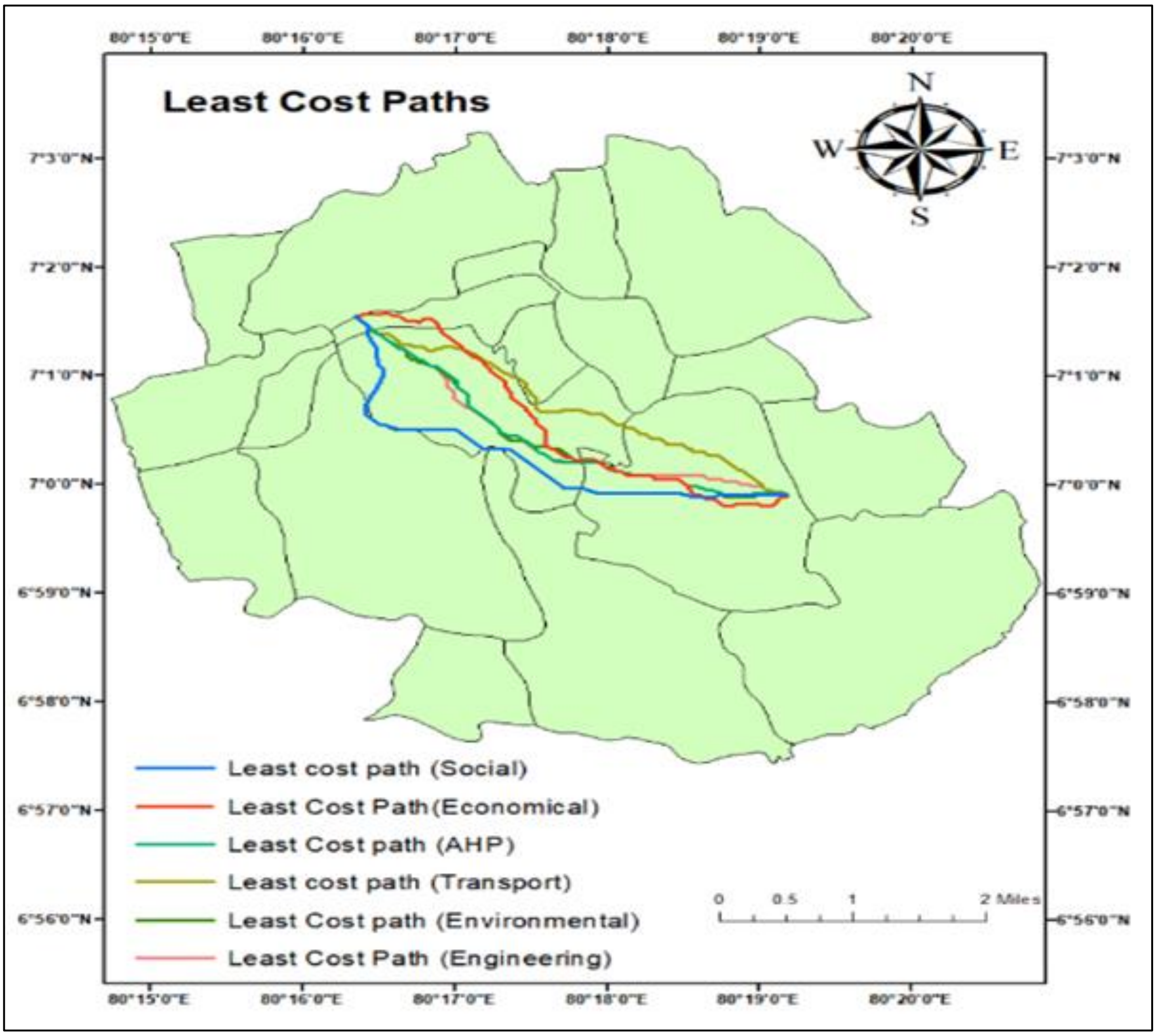

Fig 1: Six Least cost paths

➢ *Advantages of Optimal Alignment*

Except for the AHP alignment, the Engineering alignment is considerably more cost-effective according to all the assessment criteria. The Engineering alignment complies better with engineering standards and is environmentally friendly, promotes better transportation with shorter length, and is less expensive in cut and fill costs.

The most favourable optimal alignment is the Engineering alignment, which is shorter, resulting in significant savings in terms of construction cost, time, and fuel consumption. Cost savings in terms of cut-and-fill costs are impressive from an engineering and economic perspective. All these benefits make it conclusive that the optimized alignment, the Engineering alignment, is preferable, although the final decision ultimately depends on the decision maker's preference.

V. CONCLUSION AND RECOMMENDATIONS

➢ *Conclusion*

The research approach described in this study offers a specific application in the design of road alignments by utilizing GIS technology. The methodology generates optimal road alignment alternatives based on different perspectives or criteria groups, which are then incorporated into the Civil 3D CAD design process. The final assessment of the alternatives is done in the GIS platform, combining the assessment criteria from both GIS and CAD. This approach provides decision-makers with more flexibility and mitigates the landslide hazard, which can be fine-tuned to meet the specific needs of a particular geography or application.

The methodology used in this study also provides decision-makers with multiple alternatives to choose from rather than a single "optimal" solution. This not only increases the likelihood of finding a more suitable alignment but also provides the opportunity to balance different criteria, such as cost, safety, and environmental impact. Additionally, the transparency and manageability of the GIS alignment optimization system used in this study make it

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25mar1138

easier to regulate and calibrate the system to user-specific applications and stakeholder preferences.

It is important to note that the optimal alignments generated using this methodology should not be considered as universally optimal with absolute global optimization. Instead, they should be viewed as a robust indication of the best route through a region, considering various factors such as terrain, economy, environment, society, engineering aspects, and transportation efficiency. After the optimal alignment is selected, a detailed ground survey is recommended to check the alignment's real-world feasibility and fine-tune the curves to accommodate any minor adjustments required.

➢ *Recommendations*

A higher-accuracy digital elevation model would improve the precision of the vertical grade restrictions and cut and fill volume calculations. This would enhance the accuracy of the assessment and design.

To determine the weight definition for the criteria in the least cost path analysis and assessment procedure, it is recommended to use statistical methods for calculating criteria weights, such as those employed in work by Çevik & Topa (2003). These statistical index weights can then be directly used in various phases of the LCPA and assessment methodology.

To import the results of the GIS LCPA into CAD, the alignment corridor should first be exported to shapefile format and then imported into CAD. Enhancing the interoperability process between GIS and CAD would make the methodology significantly more robust.

It is advisable to conduct sensitivity analysis on the different weights to address the subjectivity and variability in the weights used in LCPA and assessment.

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