JICE Journal Innovation of Civil Engineering

Vol. 7, No. 2, pp. 306-314, 2026
Submit: 02-06-2026 |
Accepted: 14-07-2026 |
Publish: 09-08-2026 |

Evaluation of Safety Factors for the Stability of Bridge Abutments Using GEO5 on Bored Pile Foundations

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ABSTRACT
Bridge abutments are essential substructure components that transfer loads from the superstructure to the foundation and the supporting soil. The stability of abutments must be ensured, as they are subject to various loads, including vertical loads, lateral earth pressure, and traffic loads, which may affect overall structural safety. This study aims to evaluate the global stability safety factor of bridge abutments supported by bored pile foundations using the GEO5 software. The analysis was conducted using numerical modeling based on the Limit Equilibrium Method (LEM), incorporating soil investigation data, including unit weight, cohesion, internal friction angle, and the geometric characteristics of the abutment and foundation system. The analysis results show that the critical slip surface is located around the embankment and the adjacent soil layers surrounding the abutment. The calculated safety factors for five loading combinations range from 4.54 to 4.60, which are significantly higher than the minimum required safety factor of 2.50. Therefore, the abutment with bored pile foundations demonstrates satisfactory global stability and fulfills the required safety criteria against potential slope or soil failure.

Keywords: *Stability Analysis; Critical Slip Surface; Geotechnical Engineering; Limit Equilibrium; Bored Pile Foundations.*

1. Introduction

Bridges are a key component of transportation infrastructure that play a vital role in supporting regional connectivity, public mobility, and the distribution of goods and services [1]. The success of a bridge construction is not only determined by the performance of the superstructure. Still, it is significantly influenced by the substructure's ability to withstand and transfer applied loads. One of the key components of the substructure is the abutment, a structure designed to receive loads from the superstructure, resist backfill earth pressure [2], and transfer these loads to the foundation system and the supporting soil. In abutment design, stability is a critical factor, as abutments are subjected to significant vertical and horizontal loads [3]. In addition to superstructure loads, abutments are also affected by active earth pressure, traffic loads, and environmental loads, which can alter the equilibrium of the surrounding soil. If structural stability is not maintained, excessive deformation, differential settlement, and even geotechnical failure may occur, potentially compromising the bridge's function and safety [4].

Bored pile foundations are a common solution for supporting abutment structures in specific soil conditions [5]. These foundations can transfer loads to more stable soil layers at a given depth, thereby increasing the structure's bearing capacity [6]. However, the presence of bored pile foundations must be evaluated not only in terms of axial and lateral bearing capacity but also in terms of the overall stability of the soil-structure system [7]. An evaluation of global stability is crucial

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because failures of the substructure are often influenced by landslide mechanisms involving the entire soil mass [8]. Overall stability analysis is used to assess the safety of the soil-structure system against potential slip planes that may form around the abutment [9]. This analysis yields a safety factor value, which serves as an indicator of the system's ability to maintain a stable condition under various load combinations [10].

A safety factor value that meets the requirements indicates that the structure has an adequate safety margin against potential geotechnical failure [11]. Advances in computing technology have enabled more accurate stability analyses through numerical modeling [12]. One of the most widely used software programs in geotechnical engineering is GEO5 [13]. This software can model soil conditions, structural geometry, material properties, and various loading conditions to evaluate stability comprehensively [14]. The use of GEO5 offers the advantage of more comprehensive analysis capabilities compared to conventional calculation approaches, allowing evaluation results to serve as a basis for both the planning process and design verification [15].

Research on bored pile foundations generally focuses on axial and lateral bearing capacity analysis as the primary parameters for assessing foundation performance [16]. However, studies specifically evaluating the safety factor for the global stability of abutments, considering the interaction among the embankment, subgrade, and bored-pile foundations, remain relatively limited [17]. Therefore, this study was conducted to evaluate the safety factor for the global stability of abutments using GEO5 software, thereby providing a more comprehensive understanding of the safety level of the soil-structure system in supporting the sustainable performance of the bridge [18]. This study investigates the sensitivity of global stability safety factors to variations in soil shear strength parameters and bored pile geometry, providing practical design recommendations for bridge abutments founded on bored pile [19].

2. Materials and Methods

This study employs a quantitative, geotechnical analysis approach to evaluate the safety factor for the overall stability of abutment structures supported by bored pile foundations. The analysis was conducted through numerical modeling using GEO5 software, utilizing soil data obtained from field investigations as well as available structural geometric data. The overall stability analysis in this study is based on the Limit Equilibrium Method (LEM) [20]. This method is used to evaluate the balance between resisting forces and driving forces acting on the potential slip plane. The analysis results are expressed as a safety factor (FOS), which indicates the stability of the soil and structural system. The basic concept of the safety factor in the limit equilibrium method is stated as follows:

$$\left[FS = \frac{\mathrm{MP}}{\mathrm{MA}}\right] \quad (1)$$

Notes:
FS = Safety factor (2,5)
MP = Resisting Moment
MA = Driving Moment

The safety factor is calculated as the ratio between the resisting moment (Mp) and the driving moment (Ma). A higher safety factor indicates a greater ability of the soil-structure system to resist potential failure, whereas a lower safety factor indicates a lower level of stability. The higher the resulting safety factor, the more stable the slope and the soil-structure system under analysis. Conversely, a low safety factor value indicates a potential for failure due to the soil's inability to resist the driving forces acting upon it. In this study, the analysis was conducted using the Slope Stability module in the GEO5 software [21]. The modeling included the abutment geometry, soil layers, backfill behind the abutment, and bored pile foundations, which served as the structural support system.

The slope stability analysis conducted in this study requires representative geotechnical parameters as input for the numerical modeling process. These parameters were obtained from soil

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investigations conducted at the Bridge project site using the Standard Penetration Test (SPT). The soil investigation was performed to identify subsurface conditions and determine the engineering properties of each soil layer that may influence the stability of the abutment structure. Based on the interpretation of the field investigation data, several geotechnical parameters were established, including soil unit weight (γ), cohesion (c), and internal friction angle (φ). These parameters describe the soil's mechanical behavior and play a significant role in determining the soil mass's resistance to potential failure surfaces. The geotechnical parameters adopted in the GEO5 Slope Stability analysis are summarized in Table 1.

Table 1. Soil Engineering Parameters Adopted in GEO5 Modeling

Soil Layer	N-SPT	y (kN/m^3)	ysat (kN/m^3)	c (kPa)	φ (°)
Dense Sand	50	10.00	17.337	0	41

Since the subsurface material is predominantly dense sand, the cohesion value was assumed to be zero, and the soil shear strength was represented primarily by the internal friction angle. The soil profile at the study site is predominantly composed of dense sandy soil. The engineering parameters presented in Table 1 were obtained from the interpretation and correlation of SPT investigation results and subsequently used as input data for the GEO5 Slope Stability analysis. These parameters govern the soil's shear strength characteristics and directly influence the calculated factor of safety of the abutment system.

In addition to soil properties, the geometric characteristics of the abutment and foundation system also play an important role in determining the overall stability of the structure. The geometry affects the distribution of loads, the development of potential failure surfaces, and the interaction between the abutment, foundation, and surrounding soil. Therefore, the main dimensions of the abutment used in the GEO5 numerical model were adopted from the design drawings of the Besuk Bridge project. The principal geometrical parameters utilized in the analysis are presented in Table 2.

Table 2. Main Dimensions of the Abutment Structure

Parameter	Value
Abutment Height	6.0 m
Footing Width	3.8 m
Footing Thickness	0.75 m
Bored Pile Diameter	0.80 m
Bored Pile Length	10.0 m
Number of Bored Piles	8

The geometric model used in the GEO5 analysis was developed based on the dimensions presented in Table 2. The abutment has a total height of 6.0 m and is supported by eight bored piles with a diameter of 0.8 m and a length of 10 m. These dimensions were incorporated into the numerical model to represent the actual field conditions and to evaluate the abutment's global stability under various loading combinations.

To determine the safety factor and evaluate the global stability of the abutment, this study was conducted in several interrelated stages. These stages began with the collection of geotechnical and structural data, followed by the determination of soil parameters used as inputs in the modeling. Subsequently, geometric modeling and stability analysis were performed using GEO5 software to identify the critical slip surface and determine the minimum safety factor. The overall research sequence is shown in the research flowchart in Figure 1.

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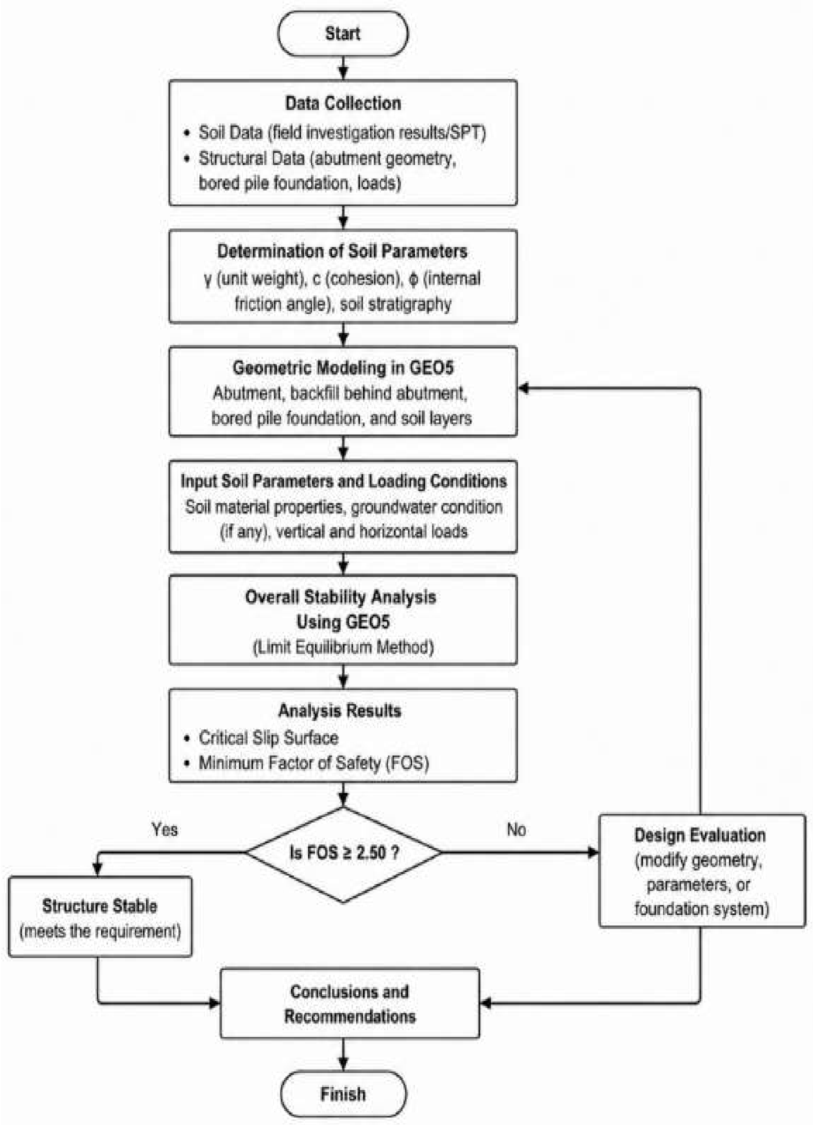

Figure 1. Research Flowchart

The global stability analysis in this study was conducted in stages to ensure that all parameters affecting the soil-structure system's stability were adequately accounted for in the modeling. The analysis process began with data collection, the determination of soil parameters, and geometric modeling, and concluded with the evaluation of the analysis results using the GEO5 software. The sequence of research steps is illustrated in the flowchart shown in Figure 1.

3. Results and Discussions

3.1. Global Stability Modeling of Abutments

A global stability analysis was performed using GEO5 software, accounting for soil layer conditions, abutment geometry, backfill behind the abutment, and bored pile foundations as the structural support system. The modeling was based on soil parameters obtained from field investigations, including soil unit weight (γ), cohesion (c), and internal friction angle (φ). The model geometry was designed to represent the soil and structural system conditions as closely as possible to actual conditions. The modeling results used in the analysis are shown in Figure 2.

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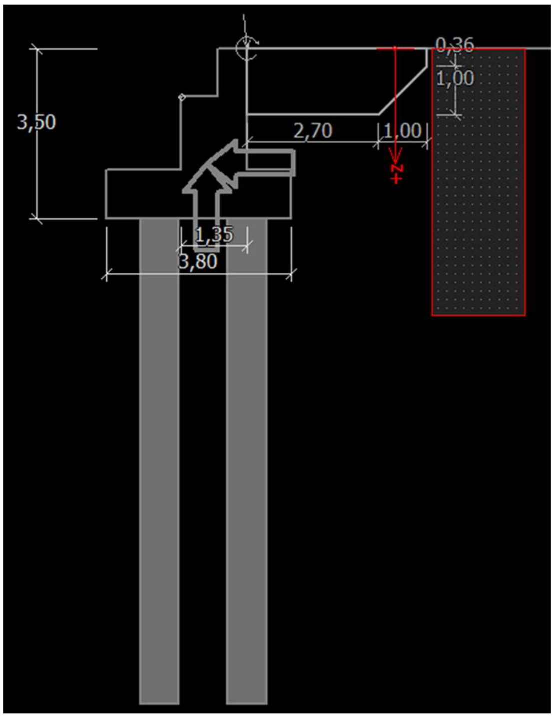

Figure 2. Modeling abutment geometry in GEO5

3.2. Results of the Overall Stability Analysis

A global stability analysis was conducted to identify critical slip planes and determine the minimum safety factor values for the soil system and the structure under analysis. The analysis using GEO5 revealed a pattern of slip planes developing through the fill area and the surrounding soil layers. These slip planes correspond to the conditions yielding the smallest safety factors and were therefore used as the basis for the structural stability evaluation. The critical slip surface identified in the analysis extends through the backfill and underlying soil layers surrounding the abutment. This condition indicates that the structure's stability is influenced by the interaction among the embankment material, foundation system, and supporting soil. Although the potential failure surface passes beneath the abutment, the bored pile foundation provides additional resistance against soil movement and contributes significantly to maintaining the overall stability of the structure.

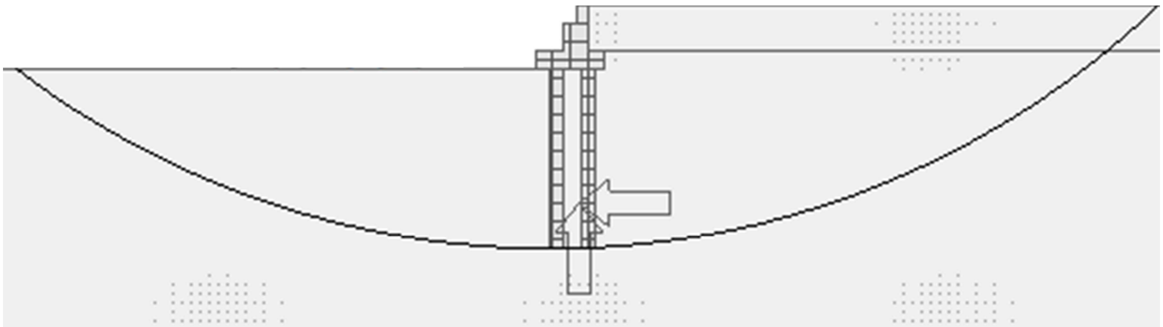

Figure 3. Results of the overall stability analysis using GEO5

Based on the results of the global stability analysis using GEO5, a critical slip surface was identified, as indicated by the yellow curved line in Figure 3. This slip surface extends through the fill area and the soil layers surrounding the abutment, potentially providing a path for soil mass movement if stability conditions are not met. The slip surface passing through the lower part of the structure indicates that the analysis treated the soil, fill, abutment, and bored-pile foundation as a single geotechnical system. The slip plane obtained from the analysis represents the most critical

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condition, yielding the minimum safety factor. Therefore, this result serves as the basis for evaluating the structure's safety level with respect to the potential for global landslides. The higher the safety factor at the critical slip plane, the greater the soil and structural system's ability to resist the driving forces that could cause failure. To quantitatively assess the system's stability, the safety factor values obtained for each load combination were evaluated. The results of the safety factor calculations using GEO5 are presented in Table 3.

Table 3. Results of Global Stability Analysis Using GEO5

No.	Combination	Ma	Mp
1	Combination 1	107081,76	486484,13
2	Combination 2	96879,46	441864,56
3	Combination 3	90893,96	414943,06
4	Combination 4	92676,40	423215,08
5	Combination 5	77956,70	358351,02

Table 3 presents the driving moment (Ma) and resisting moment (Mp) obtained from the global stability analysis in GEO5 for each loading combination. The driving moment represents the forces that tend to initiate soil movement along the potential failure surface. In contrast, the resisting moment reflects the capacity of the soil and foundation system to counteract those forces and maintain stability. The analysis results show that variations in loading combinations produce different values of driving and resisting moments. The highest driving moment was observed in Load Combination 1 with a value of 107,081.76 kNm, indicating the most critical loading condition among the analyzed scenarios. Conversely, the lowest driving moment occurred in Load Combination 5 with a value of 77,956.70 kNm. This reduction in driving forces contributes to a more favorable stability condition. The resisting moments obtained from all loading combinations remain significantly higher than the corresponding driving moments. This condition demonstrates that the available shear resistance along the potential slip surface is sufficient to counterbalance the driving forces generated by the applied loads. The relatively large resisting moments are influenced by the dense sandy soil layer characterized by a high internal friction angle and high SPT values, which provide substantial shear strength and improve the overall stability of the soil mass. In addition, the bored pile foundation system increases the resisting moment by transferring structural loads to deeper, more competent soil layers. The interaction among the bored piles, the abutment structure, and the surrounding soil enhances resistance to potential rotational and translational failure mechanisms. As a result, the stability of the bridge abutment remains well maintained under all analyzed loading combinations. Overall, the comparison between driving and resisting moments indicates that the analyzed abutment system possesses a considerable reserve of stability. The dominance of resisting forces over driving forces confirms that the foundation system and supporting soil conditions are capable of providing adequate resistance against global slope failure.

3.3. Sensitivity of Safety Factor to Loading Combinations

To further evaluate the effect of loading variations on the stability performance of the bridge abutment, the safety factor values obtained from each loading combination were examined. The safety factor is an important parameter in global stability analysis because it reflects the ratio of resisting to driving forces acting on the soil-structure system. A higher safety factor indicates greater stability and a lower probability of failure. The results of the safety factor evaluation for all loading combinations are presented in Table 4.

As shown in Table 4, the calculated safety factors range from 4.54 to 4.60. The lowest value was obtained in Load Combination 1, whereas the highest value occurred in Load Combination 5. Although each loading scenario produces slightly different stability conditions, all safety factor values remain well above the minimum design requirement of 2.50. These results indicate that the bridge abutment is adequately stable under all loading conditions considered in this study. The

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relatively small difference between the calculated safety factors suggests that the abutment system's response is not significantly affected by changes in loading combinations. This condition reflects the contribution of the dense sandy soil and bored pile foundation system in maintaining the overall stability of the structure. To provide a clearer comparison of the safety factor values obtained from each loading combination, the results are illustrated in Figure 4.

Table 4. Safety Factor Values Under Different Loading Combinations

No.	Combination	Safety Factor
1	Combination 1	4,54
2	Combination 2	4,56
3	Combination 3	4,57
4	Combination 4	4,57
5	Combination 5	4,60

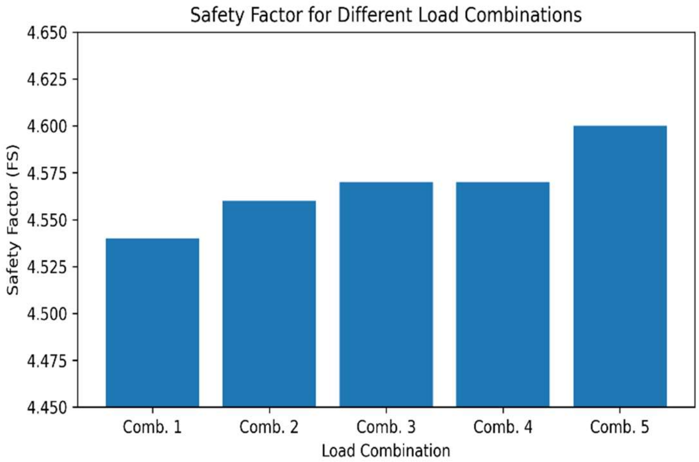

Figure 4. Comparison of Safety Factor Values under Different Loading Combinations

Figure 4 illustrates the safety factor values obtained from the global stability analysis for the five loading combinations considered in this study. The calculated safety factors range from 4.54 to 4.60, indicating relatively small variations among the analyzed loading scenarios. The lowest safety factor was observed in Load Combination 1, with a value of 4.54, while the highest, 4.60, was observed in Load Combination 5. The difference between the maximum and minimum safety factors is only 0.06, equivalent to approximately 1.32%. This result indicates that the stability performance of the abutment is relatively insensitive to changes in loading combinations. Despite variations in loading conditions, all safety factors remain significantly above the minimum required safety factor of 2.50, demonstrating that the abutment system maintains a substantial margin of safety against potential global failure. The limited variation in safety factor values can be attributed to the favorable geotechnical conditions at the site, where the dense sand layer with a high internal friction angle provides considerable shear resistance. In addition, the bored pile foundation system contributes to overall stability by transferring loads to deeper, more competent soil layers. Consequently, changes in loading combinations have only a minor effect on the abutment's global stability. These findings suggest that the stability of the analyzed bridge abutment is governed more by the geotechnical characteristics of the supporting soil and the bored pile foundation system than by variations in loading combinations.

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4. Conclusions

Based on the results of the global stability analysis of the abutment using GEO5 software, safety factors ranging from 4.54 to 4.60 were obtained for five load combinations. These values exceed the minimum safety factor of 2.50 established in the study. These results indicate that the abutment system supported by bored pile foundations exhibits good stability against global sliding. The analysis also shows that the critical slip plane formed can still be contained by the combination of soil bearing capacity and the foundation system used, thereby confirming that the structural condition is safe and meets the required stability criteria. The evaluation conducted using GEO5 modeling proves that the global stability analysis approach can provide a more comprehensive understanding of the interaction between the abutment, embankment, soil layers, and bored pile foundations as a single geotechnical system. Therefore, this method can serve as a basis for the design verification process of bridge substructures. For further research, analysis can be conducted to consider the effects of seismic loads, groundwater level fluctuations, and variations in soil conditions, to obtain a more comprehensive evaluation of the stability performance of bridge abutments.

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Vol. 7, No. 2, pp. 306-314, 2026
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