The Empirical Prediction of The Critical Area of Road Embankment Landslide Using Limit Equilibrium Method

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Abstract. This study presents the empirical prediction of the critical area for road embankment landslide. Limit equilibrium method which can also be referred to as LEM was used to obtain the factor of safety, circular centre of landslide, moment of resistance and other landslide variables. The variables used in this study were the typical soil subgrade and embankment dimension. A conclusion obtained from this study is that the safety factor is not the only determinant of the amount of embankment reinforcement needs. Other variables namely the center of landslide and delta moment resistance were also very decisive. The smallest safety factor did not necessarily result in the number of critical reinforcement requirements of landslide reinforce. In addition, the landslide area which produced the largest amount of reinforcing needs was different for each variable used in this study. This research also produced some empirical formula to determine the landslide area which produces the highest number of geotextiles from 180 trials in each variation. The empirical formula is expected to assist the designer for reinforcement needs in road embankment.

1. Introduction

Slope instability is one of the main problems facing the manmade road embankment design. The one important issue in geotechnical-civil engineering is the analysis of slope stability. It has attracted extensive attention in civil engineering and geology. Research studies [1][2] have been conducted on sliding surface searching technology in slope stability analyses since the early 1970. The limit equilibrium method (LEM) such as the ordinary method of slices [3] and Bishop simplified [4] is one very common method to analyze the stability of slopes. This method is used to analyze the slope stability with various geological engineering conditions in the field and the dimension of embankment slope [5][6]. Two steps are considered to analyse the slope stability using this method. The first step is to find the slope’s potential sliding surface position and the second step is to analyze the slope stability of the surface.

To obtain the values of the safety factor (SF) and other variables of slope stability (such us resistance moment, a radius of a landslide, etc), some formulas in the LEM have been developed in the most recent research. Moreover, many formulae have been developed to obtain the embankment critical slip surface of the landslide. The finite element method was used to locate the critical surface using mathematical optimization by [7] but this method is not commonly used for design practice. The calculation of critical slip surface is performed to find the area of embankment landslide to design the reinforcement needs. In general, the smallest SF values provides a standard for reinforcement requirements calculation. In fact, the smallest value of SF does not necessarily produce the greatest number of reinforcement needs [8][9]. Moreover, the landslide areas that exist in the field could not be
ascertained. In some cases, a landslide area with a safety factor number below one (SF<1) is found in most of the landslide trials (Figure 1). Thus, designers will have difficulties in determining which landslide area is the most critical and deserves to be a determinant in the calculation of the need for reinforcement. The uncertainty of the landslides area that may occur in this field certainly makes it difficult for designers to find the best reinforcement to ensure the safety of an embankment against sliding.

![Figure 1. Landslide area with an SF value below one (SF<1).](image)

Normally, in the stability analysis for road embankment the definite location where the critical slip surface may occur in the field is unknown. However, a critical slip surface analysis will be used by designers to determine the reinforcements for embankment if necessary. Hence, the designers assign the landslide location using the slip surface trial that is considered to occur in the field. Furthermore, there are many methods for embankment stability calculation as a standard for reinforcement design. However, Limit Equilibrium is the most commonly used and accurate method for slope stability calculation. The use of this method becomes very "uncertain" as the designers need to determine the slip surface that is considered possible in the field.

To find the accuracy of the slip surface in the field, a designer would conduct several trials. To obtain the accuracy of the results it is necessary to increase the number of trials in landslides. With the increasing number of trials, the analysis will be time consuming. Furthermore, for embankment reinforcement design, the designer often looks for the smallest SF value of landslides trial. However, according to [9], landslides are not necessarily possible in the field at the minimum SF. Thus, the smallest SF value is not necessarily the critical condition that indicates where landslide will occur first in the field. To minimize the duration of the stability analysis, designers generally conduct only approximately 1-10 trials to obtain 1-10 landslide fields and SF values. However, this number of trials is not necessarily sufficient to find out the most critical condition in a field that requires the amount of reinforcement in critical condition. A design that is produced by a small number of trials may result in an incorrect amount of embankment reinforcement requirements that is less than needed. Those inaccuracies in the calculation design are likely to be one of the causes of landslide specially of reinforced embankment. A study on the geotextile reinforcement needs of embankments that produced suggestion graph has been done by [10], but it lacks variation. A study that produced an empirical formula to determine the landslide field that produces the largest amount of embankment reinforcement has been done by the [9]. However, this research has only been carried out on relatively steep embankments (slope 1:1.5) and has not considered trapezoidal ones (slope 1:2 and 1:3) which is generally found in actuality. Therefore, further studies need to be done to get the proposed solution to reduce the problems and difficulties experienced by designers.

The main objective of this research is to develop an empirical formula to find the critical surface area of landslides for the design of suitable reinforcement under various embankment dimensions and subgrade conditions in the field. In addition, this research is also a continuation of the research study...
that was previously conducted by [9]. However, these studies have not considered the effect of the slope of the embankment. A comparison between the area of critical landslides between embankments with vertical sides and sloped sides was also carried out in this study. The results obtained are expected to find the landslide pattern that occurs on various slopes and different soil subgrade conditions so that it can be a reference for the planner in doing the reinforcement design on a landslide of embankment construction.

2. Parameters and Modelling
This research was conducted with variations of soil subgrade data and landslide area using trials. Limit equilibrium (Bishop) is the basic method used for calculations in this study. The stages of analysis in this research are as follows (see Figure 2).

![Figure 2. Research methods](image)

This present study examines a highway embankment that was constructed on soft clay foundation with a different condition. This study was carried out only on a man-made road embankment. Analyses were conducted with variations in (1) soil subgrade and (2) embankment height. Variations of soil subgrade used in this study is based on differences in soil consistency in each layer reviewed. The correlation of consistency values for clay-dominant soils is based on [11]. The variation of soil subgrade characteristics used in this research is shown in Table 1; while the embankment height varied from 6 to 7 m with embankment slopes 1:1.5; 1:2 and 1:3. For geotextile design, the formula issued by AASHTO [12] was used to calculate the number of geotextiles needed based on slope stability analysis by Bishop Simplification [4]. Some researchers have compared the use of the LEM and the finite element method. Comparisons of methods have also been performed to find which method is better suited to the actual condition of sliding. Hongjun and Longtan [13] state that the LEM is more appropriate to use to analyze landslide as well as the actual conditions of the field. Thus, in this study, the LEM is preferred based on the above-mentioned reason. For reinforcement design, A geotextile nonwoven with a tensile strength equivalent to 200 kN/m² was used in this study. Installation of geotextile on the embankment was done at 0.25 meter/layer. The geotextile was installed thoroughly on the embankment body in accordance with the number of reinforcement requirements. The increase in bearing capacity of soil subgrade is based on the formula in [14].

| Soil type | Very soft depth (m) | Soft depth (m) | Medium depth (m) |
|-----------|---------------------|---------------|-----------------|
| Type 1    | 6                   | 10            | 4               |
| Type 2    | 2                   | 10            | 8               |
| Type 3    | –                   | 6             | 14              |
| Type 4    | –                   | –             | 20              |
| Type 5 (φ = 5) | 6                     | 10            | 4               |
3. Results and discussion

This study was organized using almost 200 trials for each variation used. Bishop method for stability analysis produced the SF value, moment resistance, circular center of the landslide, and landslide area that occurred. Based on the results, the reinforcement required to retain the embankment landslide was analyzed. The landslide area in each variation which generated the largest amount of reinforcement was then used to obtain the empirical formulation. Prior to further analysis, it is necessary to analyze the relationship between the SF value and the number of reinforcements needs in each variation. The relatively similar results were obtained based on the result analysis of six different dimensions of an embankment. The chart of delta moment resistance and safety factor (Figure 3) shows that smaller values of the safety factor do not produce greater delta moment resistance. The same pattern was found on the embankment with a different slope. The greatest delta moment resistance was found at the safety factor with a middle value. Thus, the lowest safety factor value does not necessarily produce the largest number of reinforcement needs. The same results were also obtained from research conducted by [9] and [10]. The results of the number of geotextile reinforcement and the safety factor value calculation show that the landslide area that produces the largest reinforcement was not obtained from that with the smallest safety factor value. The pattern is seen in all the slope of the embankment used in this study. Such a result was obtained in soil type 1, and the same result was also obtained in another soil type which was also used in this study. These results occur at the embankment heights of 6-7 meters used in this study.

Furthermore, the relation between the number of reinforcements needs and the landslides radius shows the same pattern. The higher landslide radius does not necessarily need the most amount of reinforcement, including on small radius of landslides. Furthermore, the higher the embankment, the greater the radius of the landslide field that produces the largest amount of reinforcement. No suitable pattern has been found regarding the landslide radius with a maximum amount of reinforcement on the results of this analysis. The 180 trials were used to perform an analysis for each variation that generates the maximum reinforcement needs. A summary of landslide analyses data for each variation used is given in a graphical form. Figure 3 shows the landslide area that produced the largest amount of reinforcement requirements for embankment height 6 meters and 7 meters. The figure shows that the higher compressibility (which is the same as soft consistency) of the soil subgrade, the deeper and bigger the landslide area that occurred. The depth of the landslide area would be even greater, and the circular centre of the landslide would be further from the ground level elevation with a relatively soft clay soil consistency of the soil subgrade. The slope of the embankment also affected the results of the stability analysis obtained in this study. For soil type 4 analyses, the landslide would occur only in embankments with a slope of 1: 1.5. The other embankment slopes (1:2 and 1:3) that would be built on the soil subgrade in accordance with type 4 would not suffer from sliding.

![Figure 3](image)

**Figure 3.** Delta moment resistance, number of geotextile and safety factor results based on embankment dimension variation in soil type 1.
The landslide area that resulted in the maximum amount of reinforcement needs from the above figure was then analyzed to obtain a landslide pattern and the empirical formula. Analysis results which would be used as the main parameters in this study were the circular center of landslides and landslide areas. The analysis result of the landslide circular center can be seen in Figure 4. The circular center of the landslide on the graph is divided into 2 parameters, namely the height of the circular center of the landslide to the existing subgrade elevation and the distance of the landslide circular center from the embankment. The graph of the results in this study is distinguished based on the slope of the embankment reviewed. Some results that can be obtained from the analysis are (1) The larger the embankment slope, the greater the distance from the circular center of the slope to the subgrade elevation. The distance from the circular center of the slope from the subgrade elevation was 10-23 meters; (2) The greater the embankment slope, the greater the distance of the landslide circular center from the embankment toe. The distance of the landslide circular center from the embankment toe was 0-5 meters in 1:1.5 slope; 5-6 meters on 1: 2 and 7-10 meters slope on 1: 3 slopes; (3) The deeper the soft soil, the higher the distance of the landslide circular center from the subgrade and the farther away from the embankment toe. The embankment height also influenced the location of the landslide circular center.

The empirical formula for obtaining a range of circular center areas and landslide area on the variations used in this study can be seen in Tables 2a, 2b, and 2c. The empirical formula was obtained by using linear regression. This formula can be used if the subgrade conditions and embankment dimensions are the same as the conditions used in this study. The value range of the circular center of the landslide in this empirical formula can be used as a base to obtain the landslide area to design the needs of the amount of reinforcement in the road embankment construction.

![Graph showing landslide area](image)

**Figure 4.** The landslide area that results in the largest amount of reinforcement requirements
Besides the circular center, the location area of landslides is also discussed in this study. The location of the landslide area in this Analysis is reviewed based on 2 parameters, namely the distance from the toe of the embankment to the point which is the beginning of the landslide area and the distance from the embankment toe to the point which is the end of the landslide area (Figure 4). Some of the results obtained from the analysis are (1) The greater the embankment slope, the farther the distance of the beginning of the landslide area from the embankment toe. The greater the embankment slope, the closer the distance of the end of landslide area from the embankment toe; (2) The softer the subgrade, the greater the landslide area produced; (3) The distance of the beginning of landslide area in 1: 1.5 slope embankments were in the range of 15-28 meters from the embankment toe; 1: 2 slope was around 18-30 meters; 1: 3 slope ranged from 30 to 38 meters from embankment toe; (4) The distance of the end of landslide area in the 1: 1.5 slope embankment was around 5-20 meters from the embankment toe; 1: 2 slope ranged from 4 to 15 meters; 1: 3 slope was around 2-12 meters from embankment toe. The empirical formula produced in this study is expected to be a reference for calculating the number of critical geotextile reinforcement needs in the construction of road piles. The empirical formula generated from this research still needs to be simplified to facilitate users. This research still needs to be continually refined and the empirical formula improved.

**Table 2a.** Empirical formulae of landslide area for embankment slope 1:1.5.

| Soil type | Distance from embankment toe – left side | Distance from embankment toe – right side | Distance from subgrade elevation | Distance from the toe – right side |
|-----------|-----------------------------------------|-----------------------------------------|---------------------------------|---------------------------------|
| Type 1    | y=2x+30                                 | y=2.01x+13.18                           | y=-0.27x+21.12                 | y=1.75x-9.17                   |
| Type 2    | y=3.78x-12.46                           | y=5.14x-7.73                           | y=4x-9.27                      | y=0.27x+2.71                   |
| Type 3    | y=2.22x-7.32                           | y=7.86x-30.92                           | y=4.48x-17.71                 | y=0.41x+3                      |
| Type 4    | -                                       | -                                       | -                              | -                              |
| Type 5    | y=-1.77x+25.06                          | y=5.48x-12.35                           | y=3.3x-17.68                   | y=3x-17.26                     |

**Table 2b.** Empirical formulae of landslide area for embankment slope 1:2.

| Soil type | Distance from embankment toe – left side | Distance from embankment toe – right side | Distance from subgrade elevation | Distance from the toe – right side |
|-----------|-----------------------------------------|-----------------------------------------|---------------------------------|---------------------------------|
| Type 1    | y=0.22x+12.68                           | y=0.87x+24.02                           | y=0.54x+16.26                  | y=5.33                          |
| Type 2    | y=12.22                                 | y=2x+17.1                             | y=0.73x+13.88                  | y=0.71x+1.97                   |
| Type 3    | y=4x-20                                 | y=5.76x-16.22                         | y=4.06x-15.19                  | y=0.41x+3                      |
| Type 4    | -                                       | -                                       | -                              | -                              |
| Type 5    | y=4.67x-22.02                           | y=6.41x-16.86                         | y=5.34x-17.68                  | y=0.4x+2.94                    |

**Table 2c.** Empirical formulae of landslide area for embankment slope 1:3.

| Soil type | Distance from embankment toe – left side | Distance from embankment toe – right side | Distance from subgrade elevation | Distance from the toe – right side |
|-----------|-----------------------------------------|-----------------------------------------|---------------------------------|---------------------------------|
| Type 1    | y=-1.78x+22.68                          | y=-2.13x+49.02                         | y=0.54x+16.26                  | y=2x-4.67                      |
| Type 2    | y=-2x+22.22                             | y=2x+49.1                             | y=0.24x+17.31                  | y=2.23x-4.67                   |
| Type 3    | y=1.33x-5.98                            | y=-0.64x+33.35                        | y=0.29x+11.42                  | y=1.65x-0.94                   |
| Type 4    | -                                       | -                                       | -                              | -                              |
| Type 5    | y=-2x+22.22                            | y=-2x+47.61                           | y=0.2x+21.33                   | y=2.15x-5.49                   |

x = height of embankment
4. Conclusions
The main conclusions obtained after analyses of the variations considered in this research are:
1. As well as the results of previous studies, the lowest SF value does not necessarily result in the largest number of reinforcement requirements. The largest delta moment resistance value does not necessarily produce the largest amount of reinforcement needs.
2. Soft soil depth and embankment dimensions are very important in determining the stability of the embankment and determine the amount of reinforcement needs to withstand landslides. Dimensions of the embankment and compressible soil depth also affect the location of the circle centre of the landslide and the landslide area which result in the highest number of reinforcement needs.
3. The greater the embankment slope, the greater the distance of the circular centre of the slope from the subgrade elevation. The greater the embankment slope, the greater the distance of the landslide circular centre from the embankment toe.
4. This research produced an empirical formula that can be used to calculate the amount of reinforcement but only under the conditions where dimensions and soil parameters are almost the same as this study.

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