Optimization of Soil-Nailed Wall Design using SLOPE/W Software

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Abstract

Optimization of soil-nailed wall design can be done with adjustment on parameters and the construction elements during the design analysis. As there are many criteria in soil nailing design that could be optimized, this paper focused on three main parameters: length, inclination, and spacing of the soil nail. The aim of this paper is to evaluate the three parameters optimization reanalyses and their cost difference from the original design. The data were collected from a project in Selangor area and were reanalysed using the Morgenstern-Price Method analysis from a Limit Equilibrium software (SLOPE/W). The optimization re-analysis was evaluated with the change of the Factor of Safety (FOS) value for all cases. Results showed that reducing the soil nail length will reduce the FOS, reducing the soil nail inclination will increase the FOS, and reducing the soil nail spacing will increase the FOS. It was also known that the cost reduces from 18% to 53% in the reanalysis which showed that optimization design should be considered in all consultant firms and can be used by the clients as verification for future soil-nailed wall design.

Keywords: *Cost-Effective Design; Limit Equilibrium Method; Optimization; Soil-nailed Wall; SLOPE/W.*

1. Introduction

Soil nailing system is known to be one of the retaining structures for minimizing the risk of landslides. It is described as inactive rebar for the existing ground which can be achieved by introducing firmed separated steel bars known as ‘nails’ that are covered in grouted cement after installing a steel mesh. Soil nailing is considered to be a passive retaining structure that uses steel rods to strengthen the existing soil. These rods are installed into holes that were previously drilled in the walls and then grouted once more for securing it in place. The soil nailing system has been discussed extensively by several researchers such as [1],[2]. Some also mentioned that the reinforcement strengthened the slope stability, retaining wall, and excavation works and in order to enhance the stability of the slope, soil nailing reinforcement is grouted in place [3],[4],[5],[6]. The soil nailing method has been expanding throughout many projects since it provides cost-saving retaining wall system to hold many types of frameworks, such as the side slants of channels, impermanent vertical cuts for constructing cellar and perpetual unearthing close streets.

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There are at least three parameters of soil nailing that would affect the slope stability design and Factor of Safety (FOS). The parameters taken into consideration are soil nail inclination, spacing, and length. Dewedree and Jusoh [8] described the significant effect of soil nails inclination from a soil nailing design with different slope inclination of 30°, 45°, and 60° whereas the best FOS was found with slope inclination of 60°, 50°, and 40° respectively. This finding was supported by Rawat [9] who observed that increasing the inclination angle of soil nailing would reduce the FOS. Another study by Gunawan et al [10] stated that the FOS of a slope would increase with the increase of the length of nails in a soil nailing system. Lastly, research by A. Mohamed [11] stated that the increase in the ratio of nail length with wall height would eventually increase the FOS. He also found that nail inclination had a lesser effect on the FOS, whereas the decrease of nail spacing would eventually increase the FOS.

In this study, a project in the Selangor area constructed a soil-nailed wall system, which was then known that it doesn't have an optimized design that led to an ineffective construction cost. From the three parameters stated earlier, this study will then evaluate the three parameters with optimization reanalyses and their cost difference from the original design. This optimized design could then be a benchmark for clients in order to verify future soil-nailed wall designs.

2. Methodology

In order to evaluate the effect of soil nail inclination, spacing, and length for soil-nailed wall optimized design, a reanalysis was done with various cases from the original design. The reanalyses were done with evaluating the FOS of both the initial and optimized design slope using a SLOPE/W software from Geostudio 2012 [12] with the general method of slices developed, Morgenstern-Price Method (M-P) and Limit Equilibrium Method (LEM). The analyses were done according to the JKR guidelines and were assured to not exceed the FOS limits. The parameters of nails length, nails spacing and nails inclination were modified for each case, resulting from a trial and error for each case variable until the FOS was found to be near the limit but not yet exceeded.

Once the FOS for the five cases were determined. Cost estimation for each of the cases was calculated in order to know the cost-effectiveness of each case compared to the initial design cost. The cost estimation for each case was done with a simple Microsoft Excel tabulation with the Bill of Quantity (BOQ) of the project modelled as the main data. The process of cost estimation in the tabulation for each case can be seen in the flowchart from Figure 1 below:

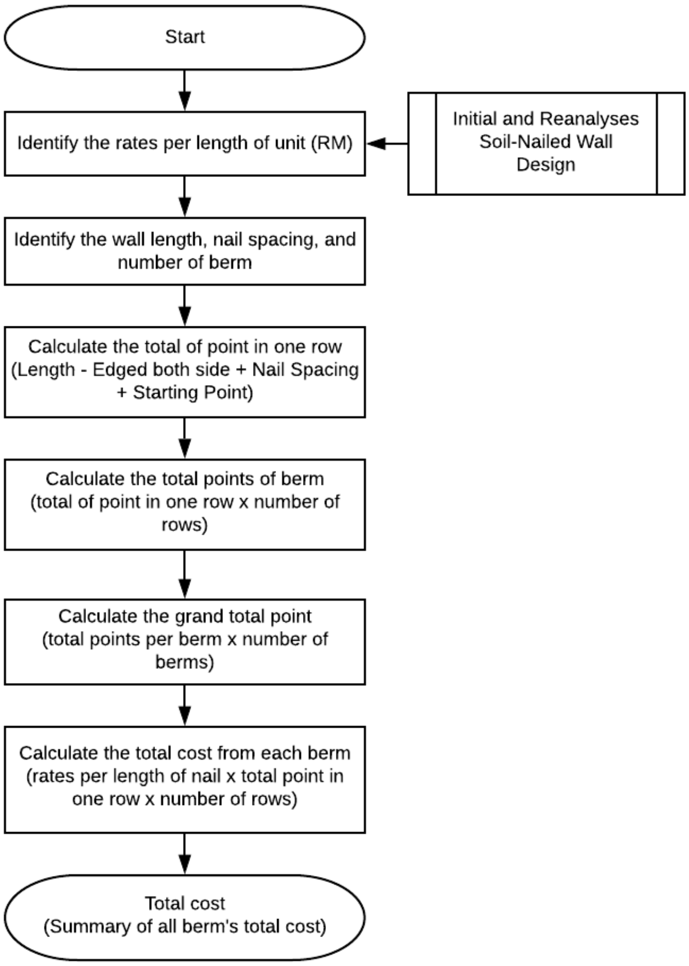


Figure 1. Tabulation process for determining the cost for each case

An optimum range of lower and upper parameters was compiled from the FHWA [13] and Geoguide 7 [7]. From there, the optimized value of the three parameters for the soil nailing can be determined as a value between the lower and upper ranges. As an example, Case 1 soil-nailed wall design had a range from lower range and upper range for its soil nail spacing, inclination, and length. For this case, the soil nail spacing of 2.0 m was selected from between 2.0 m and 1.0 m and the soil nail inclination of 20^{o} was selected from between 25^{o} and 10^{o}. As the overall height of the wall is 12.8 m, the soil nail length can be estimated to be approximately 1.2H where the H is assumed to be the wall height, which gives the soil nail length of 15.26 m and divided into three nail length of 9 m, 6 m, and 3 m selected in between the range of 15.36 m and 3.0 m. From the three processes described, optimum design and cost can be concluded for the soil-nailed wall design.

3. Reanalyses and Factor of Safety Results

3.1 Slope Stability Analyses

The modelled design example for one of the cases that include the elevation of the berms, nail inclination, and nail length of the slope before reanalyses can be seen in Figure 2. From all the cases, it was known at the end that the initial FOS was higher compared to the results from the reanalyses and adjustments. The FOS for all cases before reanalyses were known to be 1.997, 1.952, 1.813 1.648 and 1.585 whereas, after the reanalyses, the FOS were known to be 1.501, 1.512, 1.523, 1.505 and 1.554.

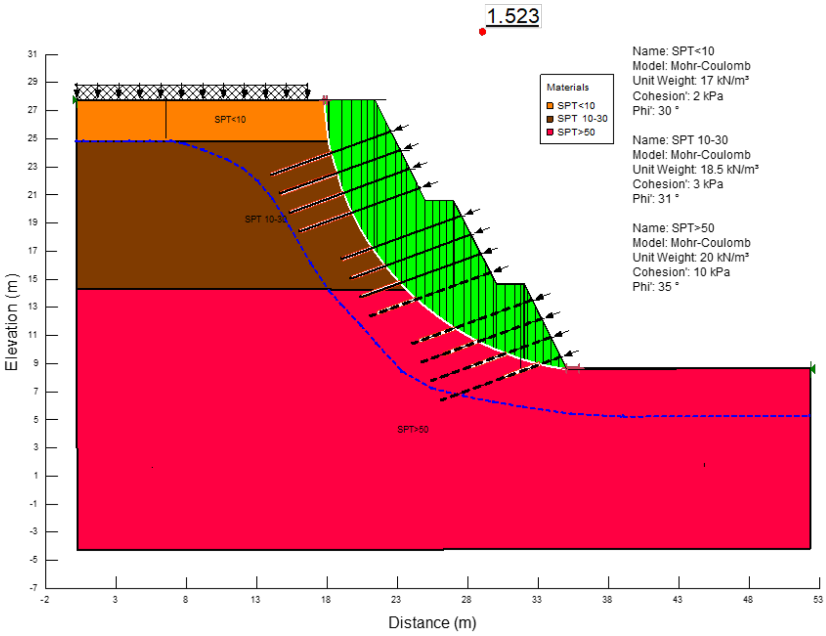
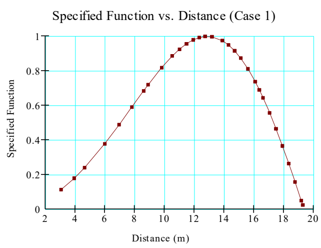
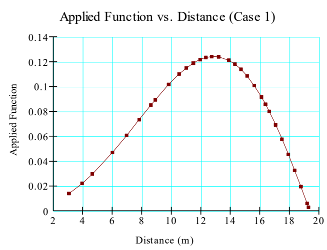


Figure 2. Elevation soil nailing design

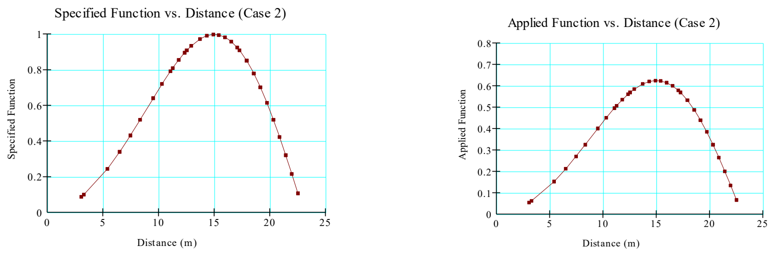
The results for all cases using the Morgenstern-Price Method for specified and applied functions can be seen in Figure 3. It can be inferred that the specified function begins at zero at each end and peaks at 1.0 near the centre of the slip surface. All the cases have the same applied function times the specified function and Lambda value. For example, the applied function for Case 1 is 0.1245 times the specified function since the Lambda value for this analysis is 0.1245. In the case where the specified function reaches 1.0, the shear to normal ratio reaches 0.1245 in the mean.



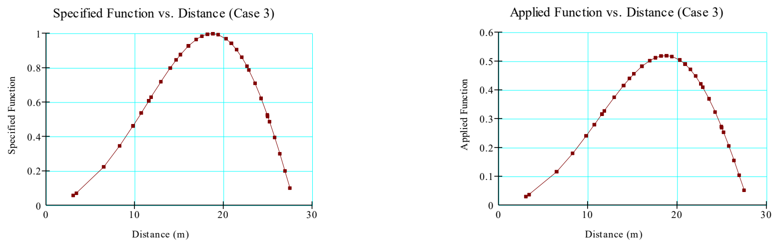
(a)



(b)



(c) (d)



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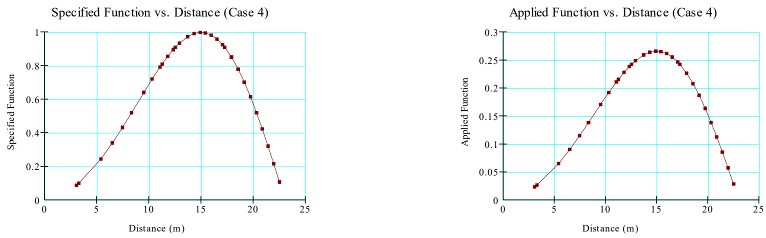
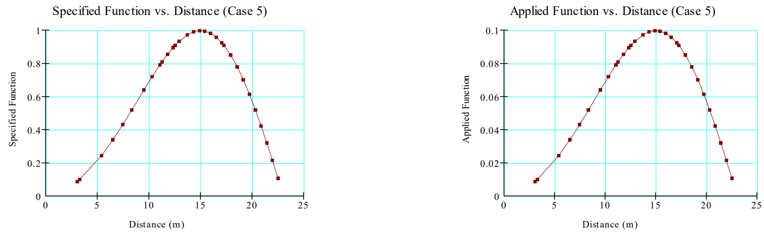


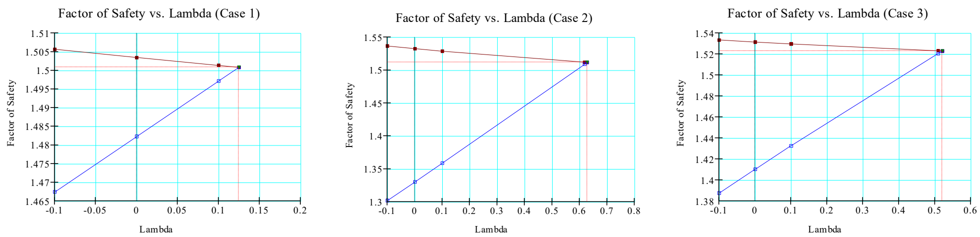
(g) (h)



(i) (j)

Figure 3. Half-sine specified for (a) Case 1, (c) Case 2, (e) Case 3, (g) Case 4, (i) Case 5 and applied inter-slice force functions for (b) Case 1, (d) Case 2, (f) Case 3, (h) Case 4, (j) Case 5

The results after the reanalyses can be seen in Figure 4 where the red line represents the moment and the blue line is the force. From the results, it can be inferred that the force and moment vary with the FOS and lambda when the two curves cross each other using the M-P Method. The force curve is at a significant slope, whereas the moment curve can be seen as mostly flat. These results meant that the force equilibrium is quite sensitive to inter-slice shear forces, whereas the moment equilibrium is quite insensitive.



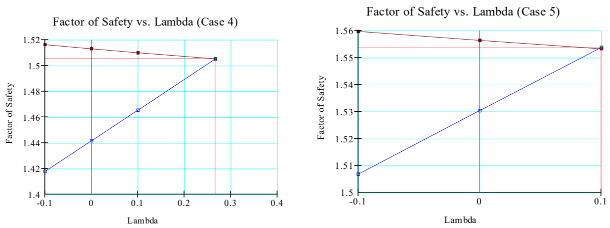


Figure 4. FOS vs. Lambda (a) Case 1 FOS 1.501, (b) Case 2 FOS 1.512, (c) Case 3 FOS 1.523, (d) Case 4 FOS 1.505 and (e) Case 5 FOS 1.554

3.2 Optimized Parameters and Rate

From all the cases, the selected nail inclination ranges from 100 to 250, nail spacing from 1.0 to 1.8 meters (m) and nail length from 3 to 15 m. Referring to Table 1, the behaviour of each case differs according to the change of the three selected parameters: soil nail inclination, the spacing between soil nails, and length of the nail.

Table 1. Parameters and nails rate for all cases

Case No.	Reanalyses	Nail inclination (degrees)	Nail Spacing (m)	Tensile Capacity (KN)	Bond Diameter (m)	Nail Length (m)	Factor of Safety	Nails Rate (RM)
1	Before	15	1.5	322	0.125	6 & 9	1.997	410, 495
	After	20	2.0	322	0.125	3, 6 & 9	1.501	205, 410, 495
2	Before	25	1.0	322	0.125	12	1.952	710
	After	20	1.5	322	0.125	6 & 12	1.512	410, 710
3	Before	15	1.0	196	0.125	12	1.813	710
	After	20	1.5	196	0.125	9	1.523	495
4	Before	10	1.5	322	0.125	12 & 15	1.684	710, 910
	After	20	1.2	322	0.125	9	1.505	495
5	Before	10	1.5 & 1.0	322	0.125	12 & 9	1.585	495, 710
	After	15	1.8	322	0.125	12	1.554	710

For Case 1, the initial soil nail inclination was 150, the spacing between the soil nailing was 1.5 m, and the length of the soil nail was 9 m and 6 m. After the optimized adjustment, the soil nail inclination was changed to 20°, the spacing between soil nail was changed into 2 m, and the length of the soil nail were 9 m, 6 m, and 3 m. It can be inferred that the adjustment of the nail length was done only at the bottom row where it was changed from 6 m to 3 m. The FOS of the optimized design was 1.501 which reduces from the initial FOS of 1.997. It can be concluded that for Case 1, increasing the soil nail inclination and spacing between soil nailing yet decreasing the nail length would lower the FOS. Similar behaviour was determined in Case 3, but with the different change of FOS from 1.813 to 1.523.

However, a different behaviour was observed in Case 2 where a different set of variables were selected for the optimized design. Case 2 showed that the FOS would decrease when the soil nail inclination was decreased, the spacing between soil nailing was increased, and the length of the nail was decreased. Another different behaviour was seen from Case 4 where the spacing between soil nailing was decreased instead. Although Case 4 was different from Case 1 to Case 3, the FOS was still optimized as it decreased from 1.684 to 1.505 which showed that the set of increasing soil nail inclination, decreasing the space between soil nailing, and decreasing the soil nail length would have no problem in achieving an optimized design with the boundary of the FOS requirement. Lastly, Case 5 was designed to increase the soil nail inclination, the spacing between soil nailing, and soil nail length. An optimized design was reached where the FOS decreased from 1.585 to 1.554.

3.3 Cost Reduction

From the reanalyses in the previous section, it can be seen that all of the cases showed a similar behaviour where the reduced FOS would eventually reduce the cost. Hence, it could be concluded that optimizing the soil-nailed wall design would result in a more cost-effective design. In order to understand the detail, Case 1 was selected as an example. In this case, before reanalysis, the design used the soil nail length of 9 m, costing RM 495.00 each and 1 no. of nail length 6 m would cost RM 410.00 each. The horizontal length of soil nailing wall is 110 m with 1.5 m nail spacing centres to centre. The soil nailing system consisted of two shotcrete berms and each berm has four rows of soil nails. There are 74 points in one row and a total of 295 soil nail points in four rows per berm. Hence, for two berms, a total of 589 points of the soil nail were determined. The cost of the first berm, second berm and the last row are RM 145,860, RM 109,395 and RM 30,203, respectively. Therefore, the total cost before the reanalysis of Case 1 is RM 285,458.

After reanalysis, the numbers of soil nail length at the first berm was not changed from 4 rows. However, the second berm was changed into 3 rows at 6 m soil nail length which costs RM 410 each, decreasing the cost of the second berm to 17.17%. Another cost reduction was achieved by changing one number of 3 m lengths of soil nailing with the cost of RM 205, resulting in a reduced cost of 50% each. Thus, it can be seen that with the system of soil nail inclination, spacing, and length adjusted together, the cost was significantly reduced to RM 189,532. Compared to the initial cost, the optimized design brought a reduction of cost up until around 33.60%. The calculated cost of the first row of the berm, the second row of the berm, and the last row of the berm were decreased to RM 109,890, RM 68,265 and RM 11,377, respectively. Hence, it can be seen that optimizing the design would lead to a lower cost than the initial design. The cost reduction for each case can be seen in Figure 5 below.

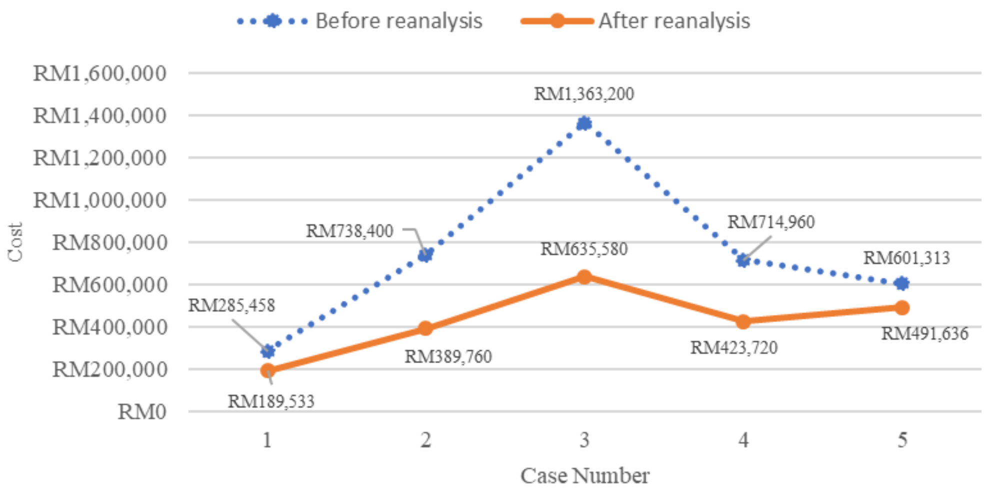


Figure 5. Cost reduction before and after reanalyses

According to Table 2 that described the change of FOS from the optimization of design, the value of the optimized design was found to be lower than the initial FOS. It can be seen that the highest cost-effective percentage was achieved in Case 3, whereas the lowest was achieved in Case 5.

In Case 3, the FOS before reanalyses were 1.813 with the cost of construction involved was RM 1,363,200. After reanalyses, the FOS was reduced into 1.523 with the cost of construction involved was RM 635,580. This reduction leads to a saving of RM 727,620 (around 53.38% effectiveness), leading to the highest cost-effective design than the other cases. On the other hand, Case 5 only showed around 18.51% cost savings. Case 5 had the lowest cost savings due to the small-scale adjustment for its optimization design, which made the cost decreased marginally. It was known that for Case 5, the soil nail length was changed only by a small margin from the initial length of 12 m, whereas the spacing was increased from 1.5 m to 1.8 m that would reduce the number of soil nailing and would eventually reduce the cost.

Table 2. Cost-saving and percentage saving

	Before Reanalyses		After Reanalyses			
Case No.	Factor of Safety	Cost (RM)	Factor of Safety	Cost (RM)	Cost Saving (RM)	Percentage saving (%)
1	1.997	RM285,458.33	1.501	RM189,532.50	RM95,925.83	33.60
2	1.952	RM738,400.00	1.512	RM389,760.00	RM348,640.00	47.22
3	1.813	RM1,363,200.00	1.523	RM635,580.00	RM727,620.00	53.38
4	1.684	RM714,960.00	1.505	RM423,720.00	RM291,240.00	40.74
5	1.585	RM601,313.33	1.554	RM491,635.56	RM109,677.78	18.24

From Table 1 and Table 2, it could be seen that reducing the soil nail length would not significantly affect the cost, the same behaviour with increasing the spacing between soil nailing at the design. Lastly, it could be seen that adding the number of nails would lead to an increase in overall cost project, but enlarging the area of retaining wall with larger spacing between soil nailing would reduce the cost.

4. Conclusion

In this paper the optimum factors considered for the three design variables: the length of a soil nailing, the spacing of soil nailing, and the inclination of the nail. These three design variables were adjusted through a method of trial and error until the optimized design within the permissible limits were achieved. The length of soil nailing was the largest affecting factor in optimizing the design, whereas the inclination of the soil nailing was the least affecting factor. However, the FOS limit was determined as 1.5 and any of the trial and error attempts were checked to have a near FOS to 1.5, but shouldn't exceed lower than the limit.

It can be concluded that reducing the length of soil nailing would reduce the FOS, reducing the nail inclination would increase the FOS, and reducing the spacing between soil nailing would increase the FOS. An attempt to optimizing the soil nailing design should also consider the bond diameter and tensile capacity in the future since it was not analysed in this paper due to its small contribution to cost-saving.

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