Stability analysis and improvement evaluation on residual soil slope: building cracked and slope failure

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Stability analysis and improvement evaluation on residual soil slope: building cracked and slope failure

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Abstract. A case study of the building and road utilities which was loading directly on the slope at IIUM, Kuantan campus was damaged due to slope failure and landslide. This research are conducted to investigate and analyze the soil properties and parameters which affected the stability of residual soil slope against failure by conducting a comprehensive laboratory testing and software analysis. The properties of soil are determined from several physical index tests and shear strength tests. Numerical simulation model from engineering software SLOPE/W were performed to show the stability analysis (Factor of Safety - FOS) of typical residual soil slope without reinforcement and new innovative design of slope with reinforcement. This paper presents two types of slope design which are single reinforcement load and combination reinforcement loads. Through this research it is proved that both single and combination reinforcement load can improve the soil properties and parameters of the residual soil slope. The new slope design successfully proved to produce positive results by achieving up to 82.49% of stability improvement (FOS) within the correct position of reinforcement load added at failure slip surface on the slope.

1. Introduction

Based on the geological map that has been overlay within this area, granite is the main rock type in this area. This granite is part of 'Eastern Coastal Belt Granite' that extends from Terengganu down to Kuantan and Johor. The granite formation at the study area is known as 'Granite Kuantan-Dungun'. Lithology or rock type of the granite is mostly made up of biotite granite. The texture of granite is fine to medium in grain size and subhedral granular.

Residual soils are product of chemical weathering which are influenced by environmental factors of rainfall or climate [1]. Tropical residual soil is a product of chemical weathering, thus its characteristics are dependent upon environmental factors such as parent rocks, climate, topography and age. This type of soil can be found in many countries all over the world, especially in the tropical region [2]. Residual soil slopes normally remain stable than sedimentary soil slope without slipping danger even with much steeper angles and they are more likely to occur only shallow curved or planar failure surfaces [2]. Slope failures or landslides are still a frequent fact, although mountains and hills are less than 25% of terrain in Malaysia [3]. Most of the hill slope failures in tropical residual soils are caused by rainfall intensity [4]. Residual soil slope failure occurred generally is caused by the increasing in pore water pressure in the slope which triggered by heavy rainfall [5]. Besides, human activities should also be the actual cause of slope failures or landslides such as slope excavation, construction activities, deforestation, or any land use etc. [6]. Weather condition (rainfall) is one of the factors that influence the soil matric suction distribution at this study area of inactive root tree zone with increasing of the moisture content and pore pressure caused to slope failure [7,8].

The aim of this research is to analyze the slope failure due to the increasing of moisture content in slope and affected by the construction of building structure developed within the middle of the slope. This paper also highlighted the innovative design by using soil-structure reinforcement load on existing failed slope to improve the factor of safety (FOS).

Figure 1. Existing Slope Location (Building & Road Damaged Signs)

2. Experimental details

Several details of the methods used in this study will be highlighted in this chapter.

2.1 Geotechnical Soil Investigation on Residual Soil Slope

The project study area is located near the International Islamic University Malaysia (IIUM), Kuantan campus. Fields observation and investigation works were widely used to study the deformation responses and failure modes of the existing slope at the study area. The stabilization of slope can be visually inspected along with the geological knowledge which is a very good method in performing the probably true stability assessment [2]. The figure shows the deformation of existing failed slope at the study area by photogrammetry and visual inspection. Geotechnical investigation involving various soil laboratory testing such as standard proctor test, particle size analysis, atterberg limits, and triaxial compression test were also conducted.

According to manual soil laboratory testing [9], standard proctor compaction test is used to determine optimal moisture content and dry unit weight for soils. The gradation or size of soil particles is determined by using mechanical sieve analysis. Atterberg limits test is conducted to gain the plasticity index from plastic limit and liquid limit of soils. Triaxial compression test or shear test (CIU) is used to measure the mechanical properties such as shear strength of the soils (cohesion, c' and shear resistance, ϕ'). The soil parameters of existing residual soil slope are shown in Table 1.

Table 1. Soil parameters adopted in slope stability analysis.

Region	Slope Description	Unit Weight (kN/m3)	Cohesion, c' (kPa)	Friction Angle, ϕ' (°)
1	Sandy CLAY of Intermediate Plasticity	19.4	9	32
2	Sandy SILT of Intermediate Plasticity	22.2	9	34
3	Silty SAND of Low Plasticity	19.9	8	35
4	GRANITE (Bedrock)		-	

2.2. Slope Stability Analysis with FOS (Numerical Simulation) by using SLOPE/W

Kinematical (critical slip surface) and Statical (equilibrium at the defined limit state) are comprised by limit equilibrium analysis of geotechnical slope stability [10]. An analytical model was proposed with the higher accuracy for the determination of factor of safety (FOS) on slope by functioning of basic geometrical parameters by using the limit equilibrium method. The increasing values of slope angle, slope height and the coefficient of variability resulted to the probability of slope failure to occur [11]. Field investigation and soil laboratory testing data were derived which resulted in the probabilistic descriptions of soil parameters that were applied in slope stability analysis. Therefore, all the relevant soil experimental data was inserted into the engineering software SLOPE/W (2007) [12] to analyze the slope stability. The slope design descriptions for stability analysis is shown in Table 2.2 while the numerical simulation slope model of actual slope profile and back analysis results with critical FOS for existing failed slope is shown in figure 2.

Table 2. Slope design descriptions for stability analysis

Slope Design Description	Unit	Remarks
Geotechnical Analysis Method	-	Bishop
Slip Surfaces Technique	-	Entry-Exit
Slip Surfaces Direction Movement	-	Left - Right
Structural Surcharged Load	kN/m3	373.36
Piezometric Level - BH1	m	93
Piezometric Level - BH2	m	93
Piezometric Level - BH3	m	76
Factor of Safety Distribution Calculation	-	Constant
Factor of Safety Tolerance	-	0.01
Number of Slices	-	30
Minimum Slip Surface Depth	m	0.1

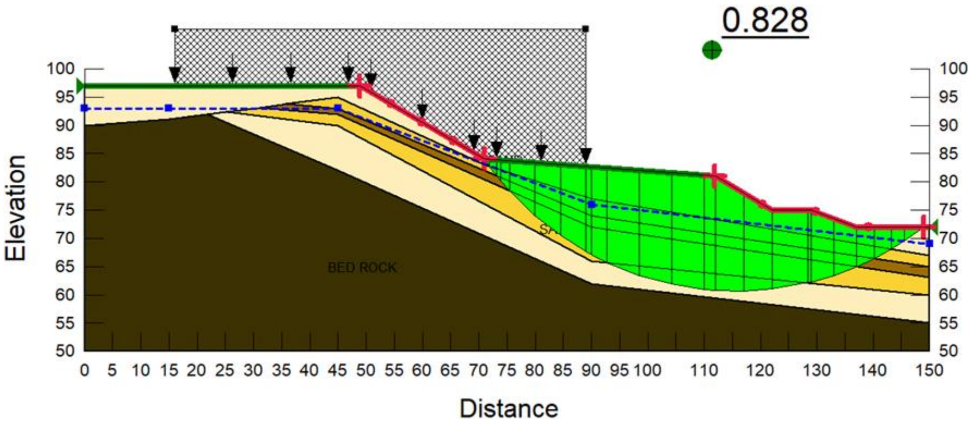


Figure 2. Back analysis results with critical FOS.

3. Slope reinforced design for stability improvement

With the factor of safety (FOS) value of 0.828, the improvement of slope was needed to overcome the failure from the building surcharge loaded slope. The range of safety factor to design the residual soil slope is between 1.3 – 1.5 [13] which is similar to the engineering manual and design from US Army Corps of Engineers [14]. The safety factor of 1.5 is the minimum requirement in this research on the stability improvement evaluation to gain higher accuracy and safety geotechnical slope designs. There are four types of reinforcement load transfer mechanism used in this research such as ground anchor [15, 16, 17], soil nailing [17, 18, 19], geo-fabric [20, 21], and driven pile [22,23]. The results of the stability analysis are summarized in Table 3 to Table 10 which included the numbers of reinforced loads and FOS value for each different types of the reinforcement load. The amount of ground anchors, soil nailing, geo-fabric and driven pile used here is to get the minimum value needed for which passed FOS by 1.5.

3.1. Slope reinforced with single reinforcement load

Table 3. Critical FOS of reinforced slope (Typical Slope + Ground Anchors).

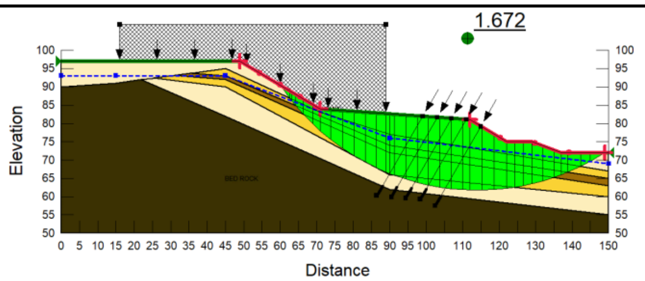
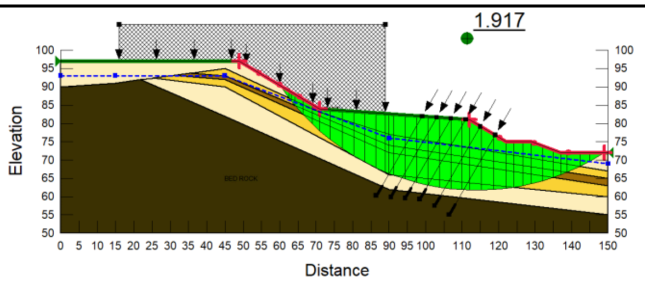
Anchor No.	Slope Model (Slope/W)	FOS Value
5		1.672
6		1.917

Table 4. Critical FOS of Reinforced Slope (Typical Slope + Soil Nailing)

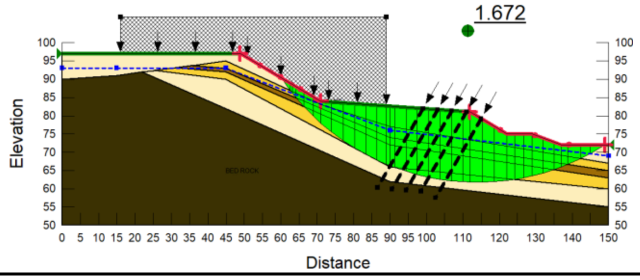
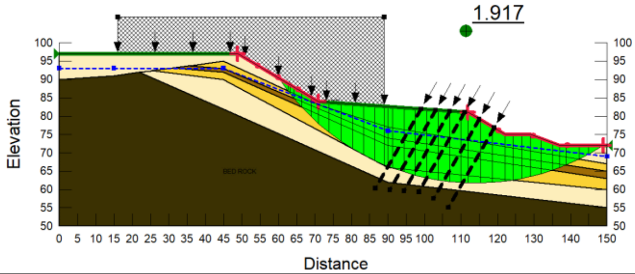
<table>
<tr><th>Nailing No.</th><th>Slope Model (Slope/W)</th><th>FOS Value</th></tr>
<tr><td>5</td><td>
</td><td>1.672</td></tr>
<tr><td>6</td><td>
</td><td>1.917</td></tr>
</table>

Table 5. Critical FOS of reinforced slope (Typical Slope + Geo-Fabric).

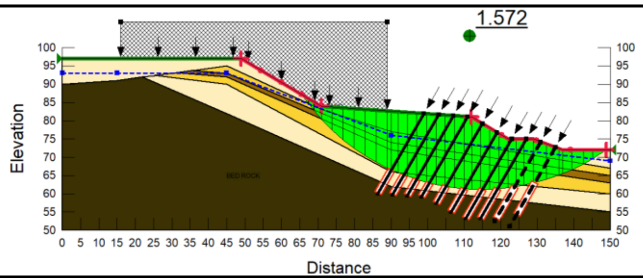
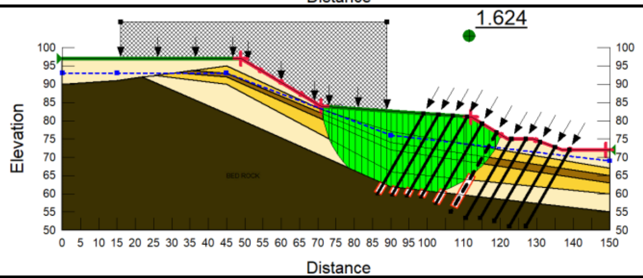
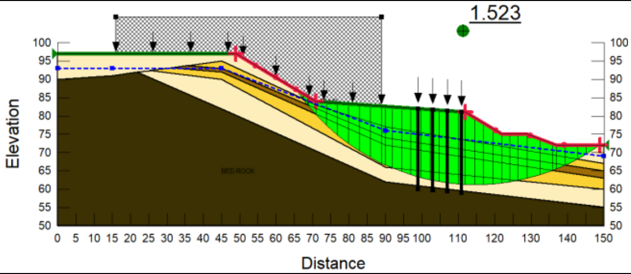
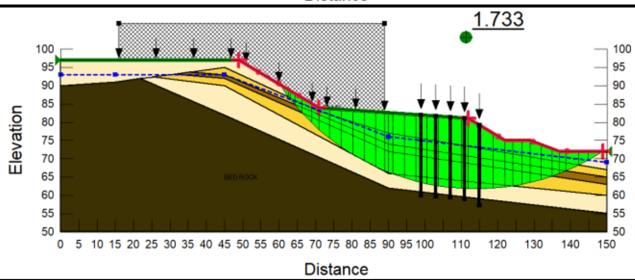
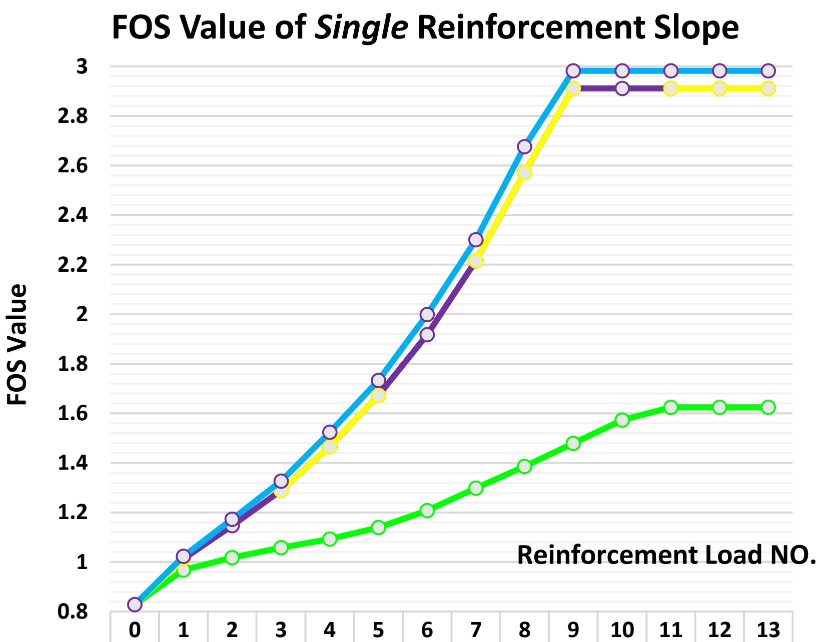
<table>
<tr><th>Fabric No.</th><th>Slope Model (Slope/W)</th><th>FOS Value</th></tr>
<tr><td>10</td><td>
</td><td>1.572</td></tr>
<tr><td>11</td><td>
</td><td>1.624</td></tr>
</table>

Table 6. Critical FOS of reinforced slope (Typical Slope + Driven Pile).

Piles No.	Slope Model (Slope/W)	FOS Value
4		1.523
5		1.733



	0	1	2	3	4	5	6	7	8	9	10	11	12	13
ANCHOR	0.83	1.01	1.14	1.28	1.46	1.67	1.91	2.21	2.57	2.91	2.91	2.91	2.91	2.91
FABRIC	0.83	0.96	1.01	1.05	1.09	1.13	1.20	1.29	1.38	1.47	1.57	1.62	1.62	1.62
NAIL	0.83	1.01		1.28	1.46	1.67		2.21	2.57	2.91		2.91	2.91	2.91
PILE	0.83	1.02	1.17	1.32	1.52	1.73	1.99	2.30	2.67	2.98	2.98	2.98	2.98	2.98

Figure 3. Design analysis results of single reinforcement slope.

3.2. Slope reinforced with combination reinforcement loads

Table 7. Critical FOS of reinforced slope (Typical Slope + Anchor + Fabric).

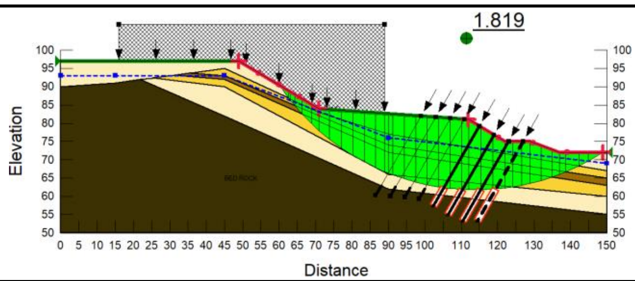
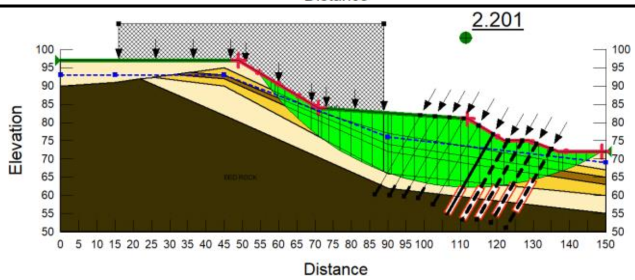
Bar No. (Each)	Slope Model (Slope/W)	FOS Value
4		1.819
5		2.201

Table 8. Critical FOS of reinforced slope (Typical Slope + Anchor + Pile).

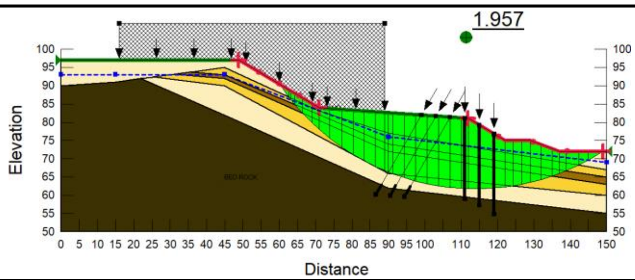
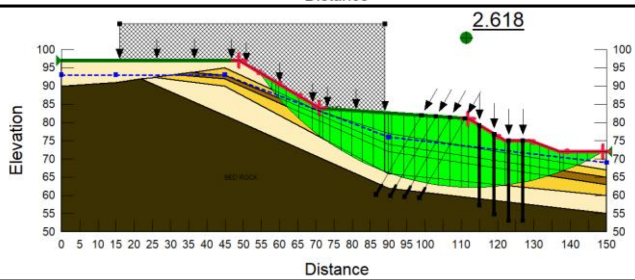
Bar No. (Each)	Slope Model (Slope/W)	FOS Value
3		1.957
4		2.618

Table 9. Critical FOS of reinforced slope (Typical Slope + Fabric + Pile).

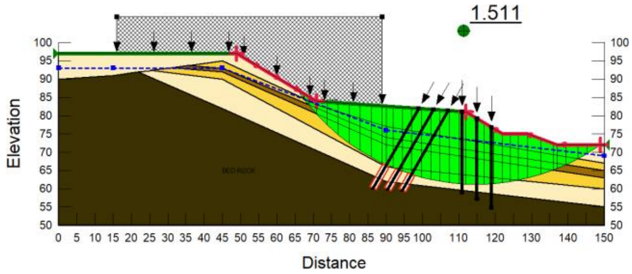
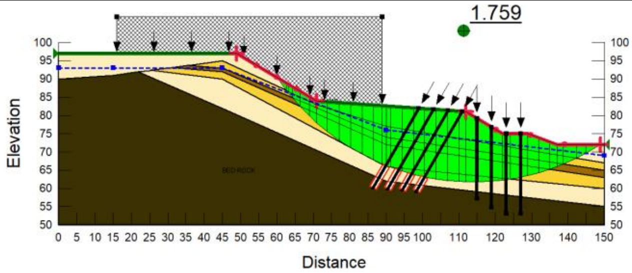
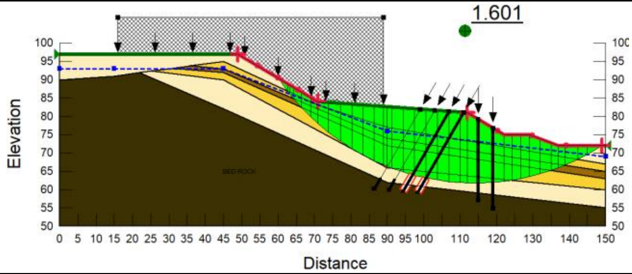
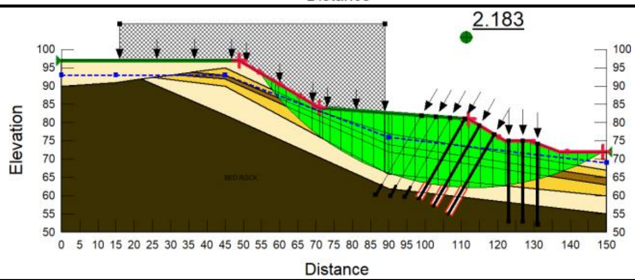
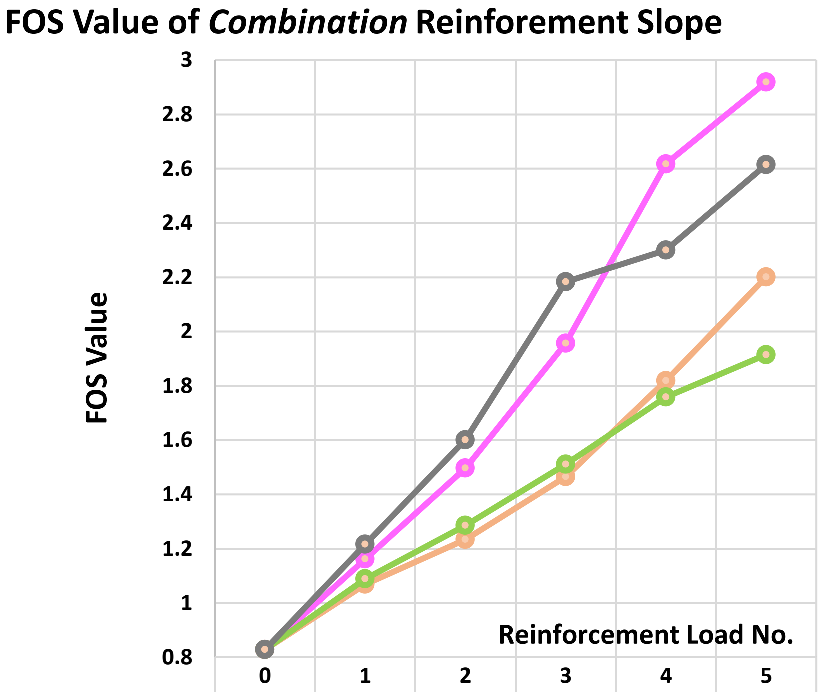
Bar No. (Each)	Slope Model (Slope/W)	FOS Value
3		1.511
4		1.759

Table 10. Critical FOS of reinforced Slope (Typical Slope + Anchor + Fabric + Pile).

Bar No. (Each)	Slope Model (Slope/W)	FOS Value
2		1.601
3		2.183



	0	1	2	3	4	5
ANCHOR + FABRIC	0.828	1.069	1.234	1.465	1.819	2.201
ANCHOR + PILE	0.828	1.162	1.497	1.957	2.618	2.919
FABRIC + PILE	0.828	1.089	1.286	1.511	1.759	1.915
ANCHOR + FABRIC + PILE	0.828	1.216	1.601	2.183	2.300	2.615

Figure 4. Design analysis results of combination reinforcement slope.

4. Slope stability improvement evaluation and discussion

Figure 3 shows the results running from analysis of SLOPE/W within the critical slip surface. All types of the reinforcement loads were proved to be increased in the stability of slope after running with the engineering software by increasing load of bars. Driven Pile is the best load to be used in soil-structure reinforcement which can be seen from the increasing trend line in graph analysis when compared to the other reinforcement loads (anchor, nailing, and fabric). Unfortunately, Geo-Fabric resulted with the lowest critical FOS value in stability improvement due to their low tensile strength when reinforced with residual soil mechanisms. Although Geo-Fabric does not increase much in slope stability, it is still considerable to be used in slope reinforced design due to the low price and eco-friendly materials with simple construction techniques. In addition, this research also came out with the innovative slope design with various combination reinforcement load between the three different types of reinforced materials (ground anchor, geo-fabric and driven pile).

This remedial design was proposed to be analyzed with the stability improvement compared to the reinforced slope of single reinforcement load. The design analysis results as shown in Figure 4 was all proved to be increased in stability improvement after reinforced with four different types of combination reinforcement load (anchor + fabric), (anchor + pile), (fabric + pile), and (anchor + fabric + pile). There are two types of combination reinforcement slope resulted in a high increasing trend of FOS which are (anchor + pile) and (anchor + fabric + pile), while the other two types of combination reinforcement slope resulted in a low increasing trend of FOS which are (anchor + fabric) and (fabric + pile) as shown in figure 4. This situation showed that the combination with Geo-Fabric caused the stability to become low owing to the low strength characteristic in soil-structure interaction. In fact, the ground anchor and driven pile are both having a high tensile strength in reinforcement bonding between residual soil and structural load. Table 11 shown the minimum slope stability improvement of FOS which passing 1.5 of safety factor which was analyzed and evaluated.

Table 11. FOS minimum increasing percentage (%).

Structural Material	Load Nos.	Without Reinforced	With Reinforced	Percentage Increased (%)
Single Reinforcement Slope				
Ground Anchor	5	0.828	1.672	101.93
Soil Nailing	5	0.828	1.672	101.93
Geo-Fabric	10	0.828	1.572	89.86
Driven Pile	4	0.828	1.523	83.94
Combination Reinforcement Slope				
Anchor + Fabric	4+4	0.828	1.819	119.69
Anchor + Pile	3+3	0.828	1.957	136.35
Fabric + Pile	3+3	0.828	1.511	82.49
Anchor + Fabric + Pile	2+2+2	0.828	1.601	93.36

5. Conclusion

Slope failures are not easily to be forecasted, thus a systematic method is needed to ensure the stability performance of slope. The soil strength properties and parameters of new reinforced slope can be seen to be higher than that of the existing failed slope after developed and proposed with the sustainable reinforcement structural loads. The suggested activities presented above are not comprehensive or perfect, but are intended to give practical suggestions to help strengthen the slope.

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