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Research Article

Study on Combined Reinforcement Technique for the Stability of Multi-Stage Slope under Surcharge Load

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Keywords

Surcharge,
Anti-slide piles,
Multi-layered soil,
Pile-anchor reinforcement,
Limit equilibrium analysis.

Abstract

Soils of varying proportions are deposited layer by layer naturally or manmade formations known as multi-layered slopes are a common phenomenon encountered in hill tract regions. A multi-stage slope located at Kutupalong Rohingya Camp in Cox's Bazar; Bangladesh was considered for the study of slope stabilization with combined reinforcement. Simplified Bishop's Method and Fellenius method were depicted at each 5° from 40° to 60° slope angle interval with Geo5 software solution. Construction over these regions or development of localization generated a progressive surcharge load at the crest of the slope. The effect of incremental surcharge load on the stability of multi-stage slope was investigated. Pile reinforcement had been proven to be an effective measure of stabilization and hence three pile positions at 2m vertical intervals were analyzed under progressive surcharge loads and its effects were studied to find out the optimal pile position. The optimal pile position improved the stability of the non-reinforced slope by around 42% to 75.5% by Bishop's method and 47% to 83% by Fellenius method. Study of combined reinforcement carried out by providing anchor support along with pile provided at optimal pile position. The anchor placement position was trialed by three different positions i.e., at each one-third of the slope height (H/3) to find out the most efficient position to support piles. An arrangement of pile-anchor combined reinforcement providing higher factor of safety when subjected to the largest surcharge load was recommended as the optimal remedial measure.

1. Introduction

Multi-stage slopes are of greater concern while analyzing for slope stability and evaluating the factors of safety. Furthermore, surcharge load on the slope has adverse effect on the stability of slope. Multi-stage slopes comprise three or more soil layers of different soil properties and encounter all over the world including the Chittagong hill tracts in Bangladesh. Soils in multi-stage slopes generally consist of residual soil, highly weathered soil, shale, or clay formations etc. that is why it is complicated to predict failure of slope [1, 2]. Numerical methods are available for Slope stability analysis and limit equilibrium analysis is the most common practice. Simplified bishop's method in LEM generally yields a Factor of Safety (FS) that is highly accurate [3, 4]. The Fellenius method can also be applied for more accurate and reliable analysis. In comparison with the other available methods of LEM, the Fellenius method generates deeper failure surface and lowest factor of safety value [5]. Six factors influence the factor of safety of a multistage slope i.e., Slope gradient of each layer, Unit weight of soil types and height of each layer have an adverse impact on FS. On contrast, Slope width, Angle of internal friction and Cohesion has an incremental effect on Factor of Safety [6]. Failure of multi-stage slope may be categorized into a local failure which is rarely encountered and overall failure due to the collapse mechanism. Collapse mechanisms are affected by the width to height ratio, step width, magnitude of earthquake and slope angle in addition to the consideration of local failure [7]. Moreover, due to ground water accumulation by infiltration causes seepage which is responsible for bulging and soil displacement [8]. Factor of safety varies with slope angle as the slope angle increases the FS decreases which indicates that the steeper the slope the more it is prone to failure. Surcharge load on homogeneous slope greatly affects the stability of slope within a certain length from crest and incremental surcharge load decreases factor of safety [9, 10]. Stability of slope is greatly improved by pile reinforcement, but it is a matter of interest to find out the most efficient position of pile and pile orientations which affects the value of factor of safety [11, 12]. Analysis by modified bishop's method showed that pile should be installed closer to the top of the slope [13]. Besides all these pile reinforcements is complex to analysis for multi-layered slope as compared to homogeneous slope [14]. Combined reinforcement is a brilliant idea to improve slope stability and available study shows that Pile-Anchor combination is most effective compared to other pile-nail or anchor- fiber combinations for homogeneous slope [15]. As the height of the anchor placement position decreases regarding the toe of the slope, the factor of safety increases. The optimal location of anchor placement is less than one third of the total height (<H/3) of the slope [16]. There is a vise-versa relationship between the thrust shared by piles and anchors which fluctuates with instability of slope. According to the pile position from toe to the crest, the thrust shared by anchors increases. To prevent excessive sliding thrust acting on anchor, piles are provided at a spacing of 2.5 times the width of pile section [17]. Based on pile-body moments, anchor tension and factor of safety (FS) a pile-anchor reinforcement performs well to stabilize a slope. A critical anchor position was encountered beneath the pile top which is approximately at 20% depth and the pile moves downward as a large shear stress is distributed. Anchor free length is suggested to be 76% of the whole anchor length otherwise larger free length may lead to elongation and deformation [18]. A pile-anchor structure is favored due to its ability to significantly diminish the risk of slope failure arising from the substantial decrease in anti-sliding force resulting from the height of the slope toe. The critical sliding surface of the reinforced slope may potentially show a failure pattern where it flows alongside or bypasses the pile-anchor structure [19, 20]. A slope

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engineering system supported by anchor bolts and piles can meet both dynamic and static stability requirements, showcasing outstanding support effectiveness [21, 22]. The limitations involved in analysis of multi-stage slope under differential surcharge condition and combined effect of Pile and Anchor in multi-layered slope can be an interesting topic to study thoroughly. Positions of piles and anchors in multilayered slope with surcharge condition is a complicated phenomenon to investigate. This analysis aims to study the effect of progressive surcharge load on multi-stage slope and to estimate the most efficient arrangement of pile-anchor combined reinforcement under maximum surcharge load. Cost efficiency is an important concern of any engineering solution hence combined reinforcement to improve stability may lead to a budget friendly stability remedy. For complex slope conditions every reinforcement is not suitable, and it is then necessary to combine or tailor two or more reinforcements together. Compatibility of using pile-anchor combined reinforcement is that it can be used with other remedial measures easily to solve more geotechnical complex slopes. Rapid installation of pile and anchor may be beneficial for emergency conditions. Engineering solutions must be long lasting and sustainable, combined reinforcement ensures long-term stability and a large life span of slopes.

2. Materials and Method

Multi-layered slopes are difficult to analyze due to varying soil properties and soil shear strength parameters. Numerical analysis i.e., simplified Bishop's method and Fellenius method were depicted to extract the factor of safety and localize the slip surface. The existence of progressive surcharge load on the crest of slope should be considered and further analysis should be done. Piles and anchors had been used as the most efficient and effective measures to improve safety which was affected by their position and arrangement.

2.1. Data collection

A multi-stage slope of Kutupalong Rohingya camp located at south-eastern part of cox's bazar, Bangladesh was considered for our stability analysis. These multi-stage slopes were higher than 10 meters with a steepness of slope angle 40° to 60° range. The average height of the soil layers was 3m residual soil fill on the top, 6.5m silty sandstone layer in middle and 2.5m bottom clay or shale layer. Shale or clay with silt and fine sand at the bottom layer had a high plasticity index of 19% to 22% which was assumed to be a clay with high plasticity layer having an undrained share strength of 50kPa as per standard classification of GEO5 software. Soil parameters of Kutupalong Rohingya Camp three layered slope were given in Table 1 below.

Table 1. Soil parameters of three-layered multi-stage slope. [2]

Soil Type	Dry unit weight (kN/m^3)	Effective Cohesion (c') (kPa)	Effective Angle of Friction (Φ')	Undrained Shear strength (kPa)
Sandy Silt with Clay	17.64	12.82	35.20°	23
Silty Sandstone	17.07	6.75	37.64°	36
Clay with Silt and fine Sand	20.50	5.00	15.00°	50

2.2. Calculation of factor of safety

The factor safety and sliding surface was investigated by Geo5 software for both Bishop's method and Fellenius method. The factor of safety was calculated for angles varying from 40° to 60° at 5° interval. The circular slip surface was divided into six slices and all the measurements i.e., width (b), height (h) and angle of inclination (α) of each slice at the bottom middle point were done graphically by the software. All the values of driving force, moment with resisting force and moment were calculated by spreadsheet and tabular analysis. The exact Factor of safety was estimated by trial-and-error method which was corrected to two decimal points.

2.3. Application of surcharge load

Surcharge load of 25 kN/m2 and 50 kN/m2 was applied along 10m from the crest of the slope. Again, the factor of safety was calculated by both methods for 25kN/m2 and 50kN/m2 surcharge load for all the slope angles. Implementation of 25kN/m2 surcharge load estimated from BNBC 2012, Part-6: Chapter-2 for single story construction showed in Figure 1 and Figure 2 shows implementation of 25kN/m2 and 50kN/m2 surcharge load considering multi-story construction.

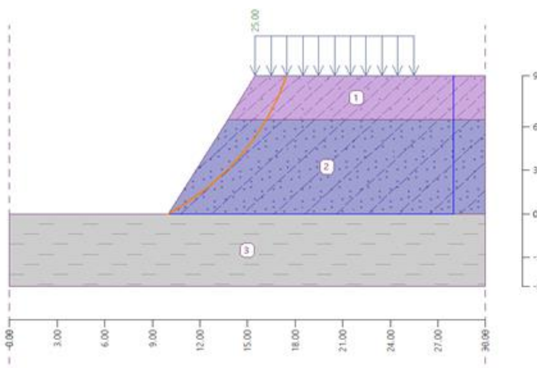


Figure 1. Slope under $25kN/m^2$ surcharge

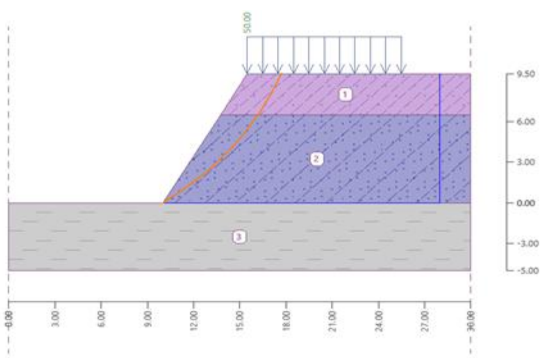


Figure 2. Slope under $50kN/m^2$ surcharge

2.4. Installation of anti-slide piles

Anti-sliding piles were used for slope stabilization which was 7.5m in length and circular having a diameter of 0.5m and pile spacing of 1.5m. The maximum bearing capacity of pile was estimated from the undrained shear strength of soil layers and the value is 400-450kN. Anti-slide piles were applied on the slope face at 2m vertical intervals and a total of three positions were considered named P-1, P-2, and P-3 shown in Figure 3. Pile position P-1 was located at the sloping top and pile toe rests on the mid part of middle layer, P-2 at 2m depth from the crest and pile toe rests on the bottom of middle layer, and lastly P-3 at 4m depth from the crest and pile toe rested on bottom shale or clay layer. Factor of safety was calculated at all three positions with zero, 25kN/m^2 and 50kN/m^2 surcharge load by bishop's and Fellenius method. By the same procedure all the pile positions were analyzed for slope angle 40^o, 45^o, 50^o, 55^o and 60^o with zero, 25kN/m^2 and 50kN/m^2 surcharge loads. Pile specifications are described below:

Length of pile, L=7.5m (According to average slope height >10m); Pile diameter, d= 0.5m (Circular pile is used); Pile spacing, s= 0.5×3 = 1.5m (Three times of the pile diameter) & Pile bearing capacity, Q= Friction capacity + End bearing capacity ≈ 400KN (estimated). Force distribution along the pile is considered constant. Passive force direction is assumed to be perpendicular to pile.

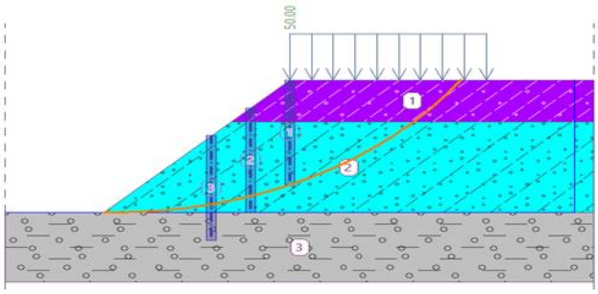


Figure 3. Pile Position P-1, P-2, and P-3 under progressive surcharge load.

2.5. Installation of anchors

Anchors were chosen as a supportive reinforcement to the optimal pile reinforcement and anchor positions at 2m intervals were selected for this analysis. Anchor arrangement A-1 was provided at 2m vertical distance from crest of slope, A-2 comprises of one row of anchor at 4m vertical distance from crest and last one A-3 was at 6m from the crest. Anchor parameters and specifications were: Free length of anchor was 4.5m, Anchor root length was 1.5m and anchor inclination angle was 20^o. The anchor spacing was 1m decided and Anchor force was estimated 500 kN according to the tensile capacity of tendon, spacing of anchor and reduction factor. Then the factor of safety was calculated under zero surcharge load to ensure the effect of anchors on factor of safety. Now surcharge loads of 25kN/m^2 and 50kN/m^2 were applied on the anchored slope and factor of safety was depicted by bishop's and fellenius method. For all the incremental slope angles 40^o to 60^o were anchored and analyzed under progressive surcharge loading. Anchor is used as a complimentary supporting measure along with piles. Anchor specifications used in the slope was given below:

Free length of anchor, l= 4.5m, Root length of anchor, l_k= 1.5m, Total anchor length, L= (4.5+1.5) m = 6m, Anchor installation angle = 20^o, Anchor spacing, b = 1m, Force, F= (Tension Capacity of tendon)/ (Anchor spacing*Reduction factor) = 500kN (estimated).

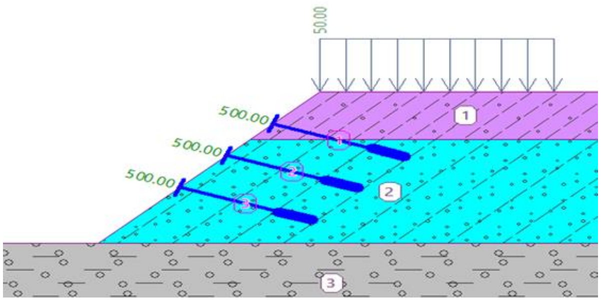


Figure 4. Anchor support positions A-1, A-2 & A-3.

2.6. Pile-anchor combined reinforcement

Three pile positions P-1, P-2 and P-3 were combined with three anchor positions A-1, A-2 and A-3 makes nine arrangements. Arrangement P-1A-1, P-1A-2, P-1A-3, P-2A-1, P-2A-2, P-2A-3, P-3A-1, P-3A-2, and P-3A-3 were possible combinations to be used as a remedial measure. As the optimal location of pile was previously encountered, the anchor support was provided only to the most effective pile position. For more efficiency, only three arrangements of optimal pile position (P-X) and three anchor positions were evaluated. Figure 5, 6, 7 shows the three combined reinforcement techniques to be analyzed for better stability.

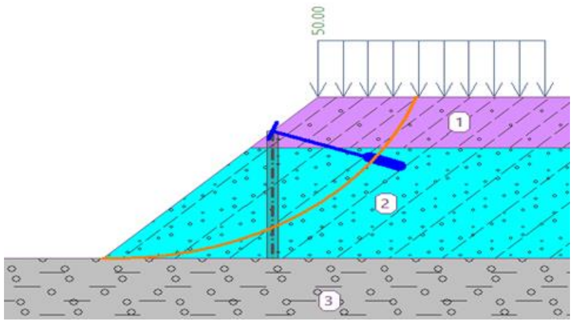


Figure 5. Arrangement P-X A-1.

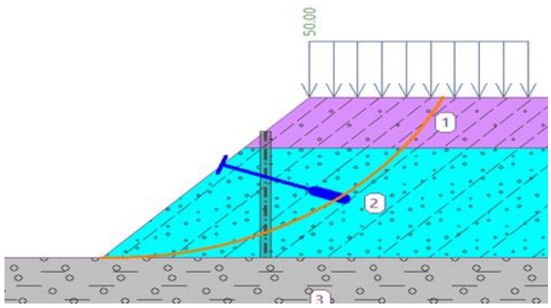


Figure 6. Arrangement P-X A-2.

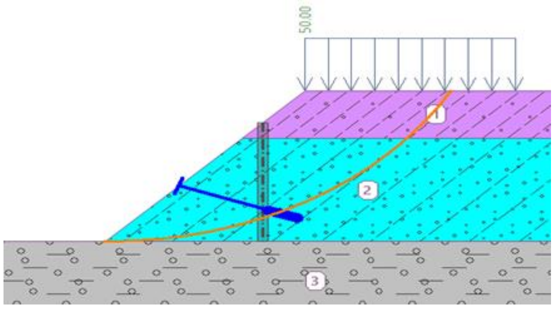
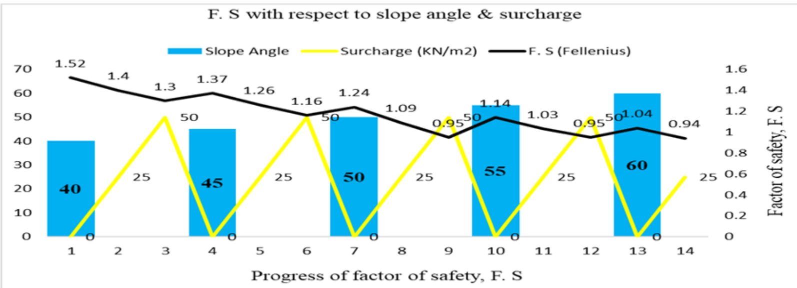


Figure 7. Arrangement P-X A-3.

3. Results and Discussion

3.1. Effects of surcharge load

Surcharge load effect, effect of pile position and combined reinforcement in multi-stage slope are discussed with graphs and pie charts. Higher factors of safety and stability were the main concern to be checked in this chapter. Figure 8 shows a graphical representation of factor of safety depicted by Fellenius method with respect to progressive surcharge load and slope angle. From the plotted graph, safety value decreases with a proportional tendency for every slope angle and the whole curve inclines down for increasing slope angle. Previous studies on homogeneous slope shows almost the same tendency of failure [9, 10]. By simplified Bishop's method safety value decreases with a proportional tendency for every slope angle same as the tendency plotted from the Fellenius method but with an almost close value.



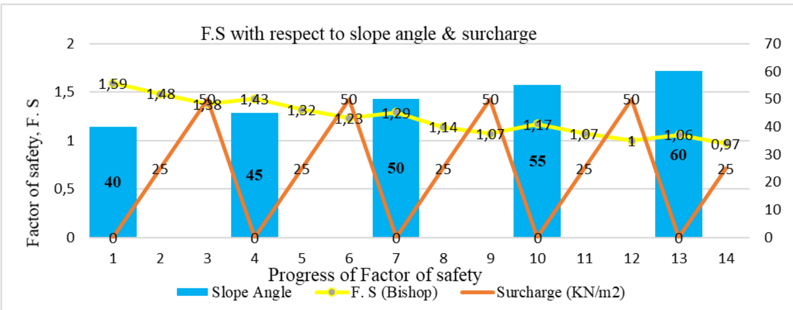


Figure 9. Graphical analysis of F. S by Bishop's method

3.2. Analysis of pile position with surcharge

The following Figure 10 & Figure 11 is a graph of F. S represented against slope angles and pile positions. From this curve, it can be estimated that for steeper slope angles (>50°) pile position 2 provides greater safety value which lies at upper middle position of slope face. Again, for low inclined slopes (<50°) pile position 2 & 3 both performed a better safety value. Although the Fellenius method depicts a slight deeper value, it also estimates pile position 2 as the optimal pile position for all slope angles under maximum surcharge load.

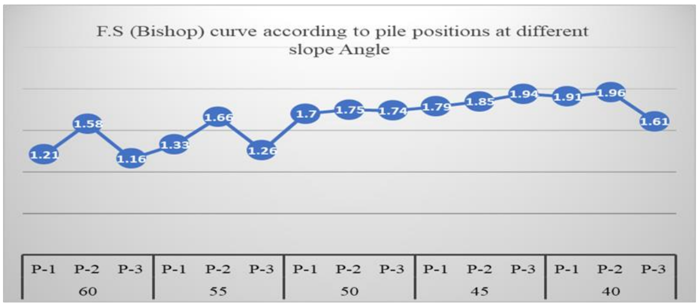


Figure 10. F. S (Bishop) value for different pile position under 50kN/m^2 surcharge

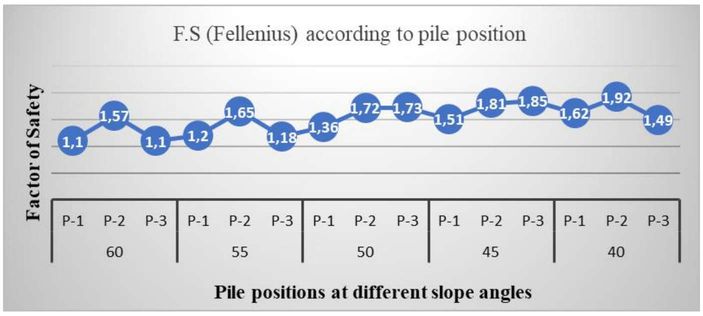


Figure 11. F. S (Fellenius) value for different pile position under 50kN/m^2 surcharge

The Factor of Safety improvement for pile position 1 (P-1) was at least 33%, P-2 was at least 42% and P-3 improved at least 17% by bishop's method under maximum surcharge load. According to the Fellenius method P-1 improved stability by at least 25%, P-2 improved 47% and P-3 improved 15% from the following Figure 12. Hence, the optimum pile position P-2 improved the stability by around 42% to 47% as compared to non-reinforced slope. A previous study on homogeneous slope showed that the stability coefficient of a slope increased near about 30% after providing reinforcement [23].

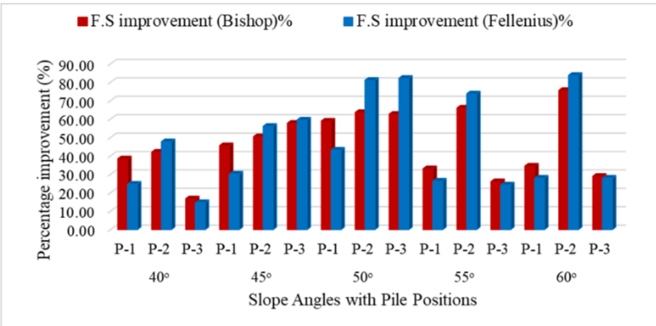


Figure 12. Stability improvement by pile reinforcement.

3.3. Analysis of combined reinforcement

All the value of factor of safety for reinforcement combinations P-2A-1, P-2A-2, & P-2A-3 under maximum surcharge load is plotted in Figure 13 by both methods. Pile position 2 when supported by anchor at 6m depth from the crest of slope i.e., Anchor position 3, ensures better safety value as compared to other arrangements which matches previous analysis on homogenous slope [12, 16]. P-2A-3 arrangement for all the slope angle performed a better stability. Fellenius method estimated a deeper value compared to simplified bishop's method for all cases. The Fellenius method estimated an exceptional case in 55° where it depicted another slip surface having an instability.

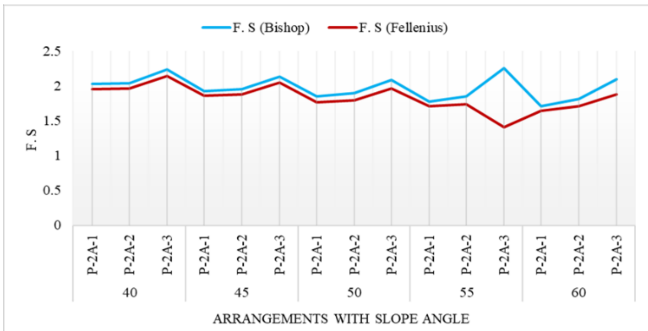


Figure 13. Results of combined reinforcement under maximum surcharge load

Improvement of the stability of pile reinforced slope by providing anchor support is shown in Figure 14. In case of lower inclined slope (≤50°), P-2A-3 brought about 14% to 19% improvement in stability according to bishop's method and 12% to 14.5% improvement by Fellenius method. For steeper slope angles (>50°), arrangement P-2A-3 showed more effective improvement in stability ranging from 33% to 36% by bishop's method and about 20% according to Fellenius method. The tendency of improvement of stability by combined reinforcement was more effective for increasing slope angle.

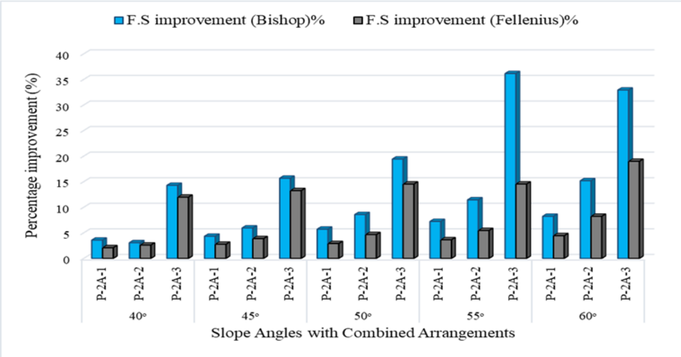


Figure 14. Improvement of factor of safety for combined reinforcement

Improvement of the stability of non-reinforced slope by the application of pile-anchor combined reinforcement is shown in Figure 15 with different slope angles under 50 kN/m^2 surcharge.

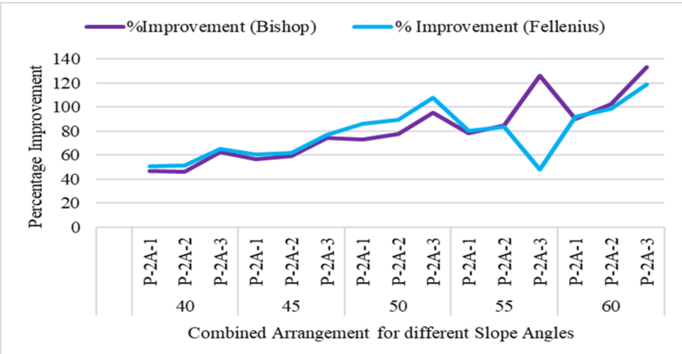


Figure 15. Improvement of non-reinforced slope by combined reinforcement

From the graph plotted in Figure 15 it can be estimated that pile-anchor combined reinforcement improved the stability of the lower inclined slope (θ<50°) by around 50% to 75% and for steeper slope angles (θ≥50°) stability increases near about 90% to 120%. It means that pile-anchor combined reinforcement can improve stability more than two times than that of the natural condition.

4. Conclusions

This study was conducted to identify remedial measures for multi-stage slopes located at Chittagong hill tracts in Bangladesh. Pile-Anchor combined reinforcement was referred to as the best engineering technique to maintain stability of slope for a long period of time. Positions of pile and Anchors had a huge impact on the safety values and location of sliding surfaces.

Reinforcement positions, progressive surcharge effects and combination of reinforcement had been studied thoroughly which lead to the following findings:

- Factor of safety curve exhibits a proportional inclination to decrease as the slope becomes steeper and as the surcharge load increases using both approaches. Progressive surcharge load on top has a tendency in general to enlarge the radius of curvature of circular sliding surfaces.

- For gently inclined slopes (≤50°) pile position-2 (P-2) and pile position-3 (P-3) performed a relatively better stability but in case of higher inclinations (>50°) only pile position 2 (P-2) generates highest stability. The pile position 2 (P-2) improved the stability of the non-reinforced slope by around 42% to 75.5% by Bishop's method and 47% to 83% by Fellenius method. Hence, P-2 proved to be the optimal pile position.

Combined reinforcement was more efficient when pile installed at optimal position and supported by anchors. A deeper anchor placement location served more stability as anchor was to be then able to hold back a larger sliding soil mass. Combined reinforcement arrangement P-2A-3 improved the stability of pile-reinforced slope by at most 19% to 36% under maximum surcharge effect considering both methods and could be recommended for higher safety values and better stability. Stability of a non-reinforced slope under maximum surcharge load could be improved by around 50% to 120% by pile-anchor reinforcement.

Recommendations

- Earthquake load effects and seepage effects due to heavy rainfall are not considered for this analysis. So, further study will be recommended.
- Effects of vegetation on sloping surface and wind load effects should be investigated further for more accuracy.
- Finite element method will be used to calculate FS.
- Drained-undrained conditions will be considered.
- More slice will be created.
- Cost analysis will be added.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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