Stability Analysis of Rock-Socketed Piles on Inclined Slope: Case Study on Conveyor Belt Foundations of Dangote Cement, Ethiopia

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Research Article

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ABSTRACT

This study was carried out the stability analysis of rock-socketed pile on inclined slope at Dangote Cement (Ethiopia) around C1-12A, C1-13A and C1-14A Conveyor Belt foundation. The Conveyor foundations were founded on the natural inclined slope which passes through rugged topography and faces frequent slope stability problems.

The study identified and analyzed the stability of slope by determining the geological and geotechnical properties of materials which compose the critical slope section.

Detailed field work was done to collect a sample for laboratory tests such as moisture content, grain size analysis, Atterberg limit, compaction test and direct shear test. Based on the field manifestations and secondary data from different sources the critical slope section was identified for stability analyses. The slope stability analysis was made by three-dimensional finite element method, Rocscience based RS3 software.

The slope stability analyses in terms of safety factor for both dry and saturated condition were analysed.

The analysed results showed that, for saturated conveyor belt with rock-socketed pile, the factor of safety was 1.648 and stable. Even though, the factor of safety was stable, it was deducted from 3.698 for dry condition to 1.648 for saturated condition. Therefore, the stability of rock-socketed pile on inclined slope was highly depending on the raising of ground water table in the rainy season.

Based on the identified slope stability governing factors, the proper drainage system such as surface drainage (i.e. furrows and ditches) which can prevent infiltration of rainfall and flood into the slope and subsurface drainage (i.e. horizontal and inclined drain pipe) which reduce the raising of groundwater was recommended. The stability of pile foundation in terms of bearing capacity, settlement, lateral resistance and pull-out capacity of grouped pile were analyzed using RSPile software and hand calculations. The analyzed results showed that, the pile foundation was safe against bearing capacity and uplift failure.

The maximum displacement of grouped pile was less than the maximum permissible displacement and the maximum lateral deflection was less than the permissible lateral deflection allowed for grouped pile.

Keywords: Slope stability analysis; Rock-socketed pile; FEM; RS3; RSPile; Stability analysis of pile foundation; Slides

INTRODUCTION

A slope is defined as a ground surface that positions at an angle to a horizontal level. Slopes may be creating from the natural or usually by people. An earth slope is an unsupported, inclined surface of a soil mass [1]. Each slope has singular soil properties and geometric features, which try to resist soil gravity or failure. Slope collapse cause the soil body to transfer downward and outward usually happening slowly or rapidly without attention. Slides generally start from hairline tension cracks, which propagate inside the soil layers [2].

Slope stability problems are frequently encountered in the construction of roads, canals and dams as well as some natural slopes are may become unstable due to the presence of water which weakens the soil characteristics or due to an excavation. The slip of a slope can be catastrophic and causes human losses in addition to considerable natural damages. [3].

Instability related issues in engineered as well as natural slopes are common challenges to both researchers and professionals. In construction areas, instability may result due to rainfall, increase in groundwater table and change in stress conditions. Similarly, natural slopes that have been stable for many years may suddenly fail due to changes in geometry, external forces and loss of shear strength [4].

The failure of slopes takes place mainly due to the action of gravitational forces, and Seepage forces within the soil [1]. In addition, the long-term stability is also associated with the weathering and chemical influences that may decrease the shear strength [4,5].

The engineering solutions to slope instability problems require good understanding of analytical methods, investigative tools and stabilization measures. One says, “The primary aim of slope stability analyses is to contribute to the safe and economic design of excavation, embankment and earth dams” [4].

The rock-socketed pile is a large diameter pile, widely employed as an important form of bridge foundation in regions characterized by complex engineering geology, such as rivers, lakes, and valleys [6].

In this study, large diameter bored rock-socketed piles are being used to carry heavy loads from Conveyor Belt (Figure1). The total length of the Conveyor Belt is about seven kilometres for Dangote Cement Factory to quarry area in order to transport limestone from quarry to the Factory. The vertical, long, bored, end bearing and reinforced concrete pile were used for this study.

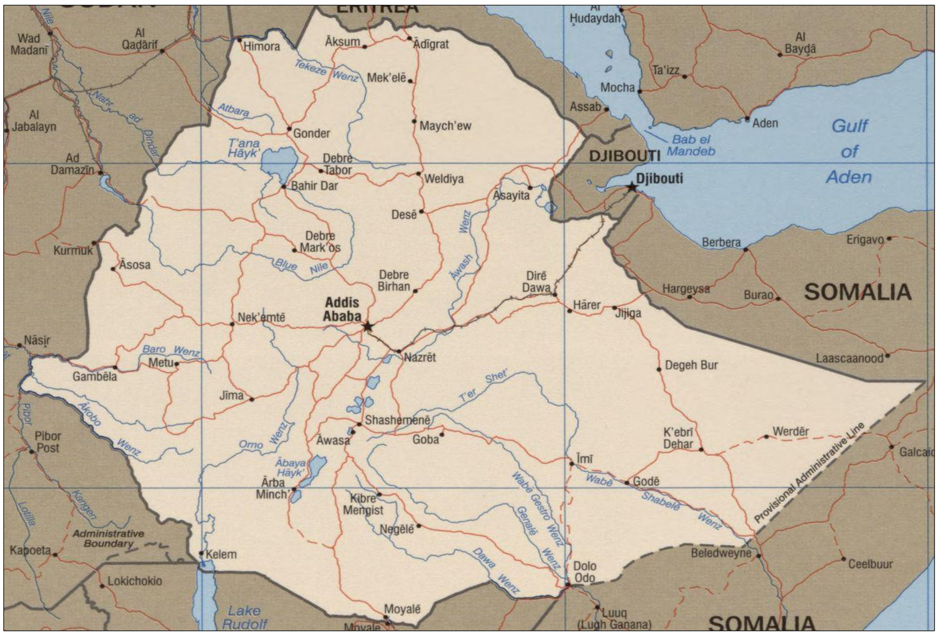
Figure 1. Conveyor belt of Dangote cement on inclined natural slope.

MATERIALS AND METHODS

Location and accessibility

The case study area is located in regional state of Oromia, at Mugher town, Ethiopia (Figure 2). The area is accessible by Asphalt road leading to Mugher cement enterprise, *via* Mugher town, about 90 km west from Addis Ababa. The area is bounded by geographical coordinate latitude 9°15’00”N to 9°30’00” N and 38°20’00”E to 38°30’00”E, in the Northwestern Ethiopian Plateau [7].

Figure 2. Location map of the study area.



Geology of study area: Mugher valley is part of Blue Nile Basin situated in the Northwestern Ethiopian Plateau. The E and SE part of the area is bounded by the tectonic escarpment of the uplifted western flank of the Main Ethiopian Rift. It is also bounded by the Axum–Adigrat and Ambo-Nekemte lineaments to N and S directions respectively. The Blue Nile Basin contains about 1400 m thick section of Mesozoic sedimentary rocks that un-conformably overlying NeoProterozoic basement rocks and un-conformably overlain by Early-Late Oligocene and Quaternary volcanic rocks [8].

The type of soil and rock on study area: In the study area, there is huge amount of surface soil covering the bed rocks. The stiff light brown gravelly silty soils are found from depth of 0 m–0.5 m. The dense dark brown silty sandy gravel soils are found from depth of 0.5 m–5 m. The strong dark grey fine grained basalt (boulder) covered the depth of 5 m–5.6 m. The dense dark grey fine grained sand found at depth of 5.6 m–5.8 m. Medium strong dark grey fine grained highly fractured and moderately weathered basalt covers depth of 5.8 m–6.3 m. The dense dark brown sandy gravel found from depth of 6.3 m–9 m. Very stiff light orange to whitish brown clayey silt soil are found from depth of 9 m–13.3 m. The weak white limestone from 13.3 m–13.5 m.

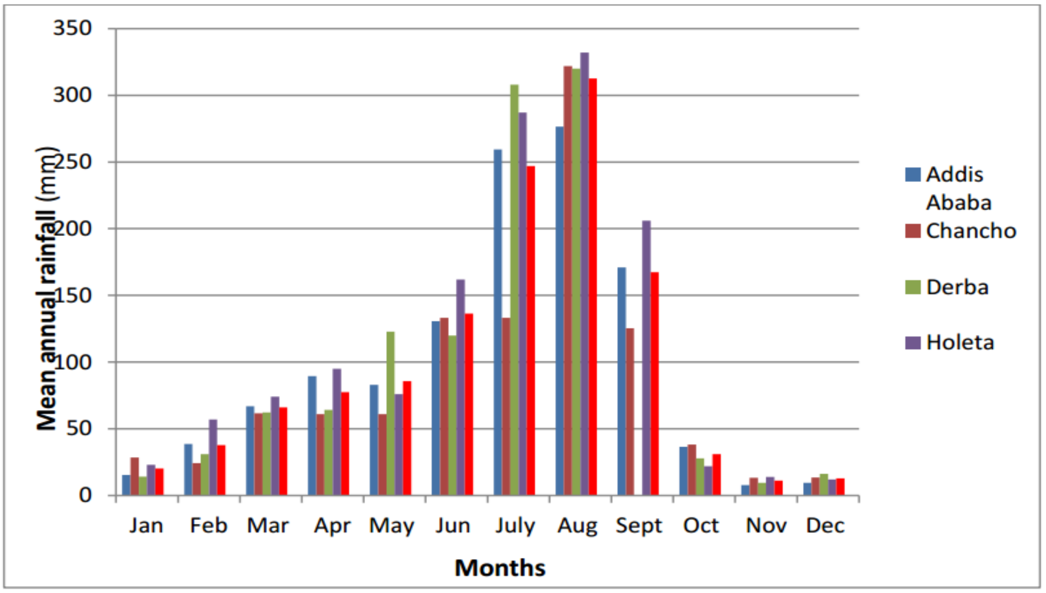
The light to orange brown highly weathered marl/shale depth is 13.5 m–15 m and orange to dark brown highly weathered marl/shale depth is 15 m–18.2m. The medium strong dark grey fine grained slightly weathered and highly fractured basalt rocks are found from depth of 18.2 m–22.4 m.

Climate: Study area falls under sub-tropical climatic zone with the highest rainfall occur between June and September [7]. Another smaller rainy season is also known between February and May, however, in the study area rainfall amount is generally low. Two rainy seasons are known in the area those are summer and winter (Table 1 and Figure 3).

Table 1. The mean annual rainfall of the surrounding area [7].

Area	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Addis Ababa	15.5	38	66.8	89.4	83	130.7	259.5	276.5	170.9	36.5	7.9	9.5
Chancho	28.5	24	61.6	61	61	133	133.2	321.8	125.3	38.1	13.3	13.5
Derba	14.2	31	62.2	64.1	122	119.8	307.9	320.1	159	27.8	9.5	16.2
Holeta	23	57	74	95	76	162	287	332	206	22	14	12

Figure 3. Mean annual rainfall around the study area [7]. **Note:** ■ Addis Ababa, ■ Chancho, ■ Derba, ■ Holeta.



Pervious related studies

Griffiths and Marquez studies the three-dimensional slope stability analysis by elasto-plastic finite elements. They demonstrate some 3D slope stability analyses by finite elements, placing the results in context with 2D solutions and validating the results where possible against alternative methods. The 'Iterations' column displays the number of iterations needed for convergence. As the factor of safety is approached, the algorithm has to work harder to reach convergence, as seen by the increase in the number of iterations. When SRF ≈ 1.73 the analysis was unable to converge within 1000 iterations, and a sudden increase in the dimensionless displacement was observed. At this point FS ≈ SRF and the factor of safety using CLARA is given by FS ≈ 1.73 [9,10].

Jeremic studied the finite element methods for 3D slope stability analysis. A new approach for modeling of three dimensional slope stability problems is presented [11]. The analysis shows that the factor of safety using FEM for the 450 curved slope is FS=1.65. In the case of 900 curved slope the safety factor (first occurrence of the limit point or beginning of softening behavior) using FEM is at FS=1.38. This represents a significant reduction from a value of 2.0 obtained by the method of slices (widely used in practice).

Matsui, et al. performed the finite element slope stability analysis by shear strength reduction technique. The slope failure is defined according to the shear strain failure criterion [12]. The detailed background behind the shear strength reduction technique, the elucidation of the physical meaning of the critical shear strength reduction ratio in regard to the total shear strain and shear strain increment for both embankment and excavation slopes and its practical application to a field test on a reinforced slope cutting are presented. Based on the local safety factor, the safety factor along the minor failure slip surface was calculated by using the shear strength reduction technique to be 1.02. Based on the local safety factor surface and the slip surface traced by the shear strength reduction technique, the safety factor of the reinforced slope was calculated to be 1.12.

Sainak, et al. studied the application of three-dimensional finite element method in parametric and geometric studies of slope stability analysis [13]. Some of the capabilities of the finite element method in the slope stability analysis are investigated and compared with the traditional limit equilibrium techniques. A procedure of calculating factor of safety from 3-D finite element analysis is also described. The procedure is implemented in parametric and geometric studies carried out on soil embankments to examine the influence of factors such as: geometry of embankments, curvature and pore water pressure on the resulting values of factor of safety. Two commercial finite element packages: PAFEC and CRISP were used. Finite element method using PAFEC factor of safety is 0.95 and using CRISP factor of safety is 0.93. Analyses using different finite element commercial programs result in very similar displacement values and factors of safety.

Su, et al. studies a three-dimensional slope stability analysis method based on finite element method stress analysis. The finite element method with a linear elastic ideal plastic model is used to calculate the stress [14]. This calculation is performed with the commercial finite element software Abaqus 6.14. The ideal plastic yield criterion is consistent with the Mohr-Coulomb failure criterion. The safety factors computed by stress-based method are 2.226. The stress is affected by material parameters, geometric models, boundary conditions and loads, while the stress affects the minimum safety factor and the associated slip surface.

RESULTS AND DISCUSSION

Modeling with FEM (RS3)

Geometric modelling: The critical sections of the rock-socketed pile on inclined slope were used for RS3 modeling as shown in Figure 4 and Table 2.

Figure 4. 3D geometry of modeling.

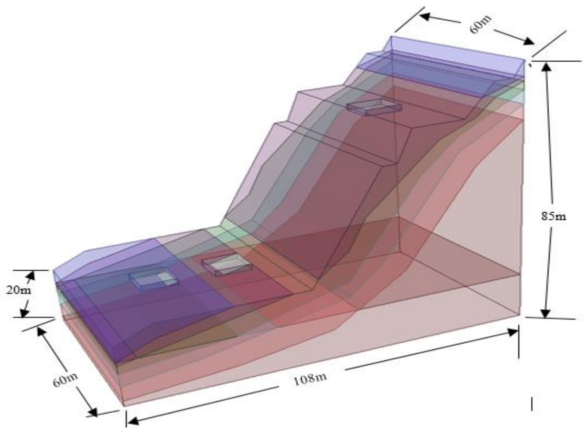


Table 2. Geometry of the slope.

Symbol	Slope height (m)	Slope width (m)	Slope angle (deg)
θ_1	5	10	26.6
θ_2	35	20	60.3
θ_3	10	4	68.2
θ_4	10	8	51.3
θ_5	5	3	59

Material modelling: The mechanical behaviour of soils and rocks can be modelled with various degree of accuracy. For this study, the elastic perfectly plastic Mohr-Coulomb model was used. Rock layers were modelled using Hoek-Brown equivalent Mohr-Coulomb model. The model uses E and v as soil elasticity, φ and c as soil plasticity and ψ as angle of dilatancy. Slope stability analysis is relatively unconfined, so the choice of dilation angle is less important [9]. As the main objective of the current study is the accurate prediction of slope factors of safety, a compromise value of ψ =0, corresponding to a non-associated flow rule with zero volume change during yield, has been used throughout this paper. The model does not include stiffness varying with stress and strain. The effective soil and rock parameters were summarized in Table 3 were used for this modelling.

The material behaviour type used for this study was dry and saturated condition and the stiffness type are linear isotropic. Both peak and residual strength were used for shear strength reduction method.

Table 3. Soil and rock parameters used in numerical modeling.

Layer no.	Types	Depth	Cohesion (kPa)	Friction angle (0)	Unit weight (kN/m³)	Modulus of elasticity (MPa)	v
1	Silty sandy gravel	0-5	80.33	38.5	16.85	20	0.25
2	Sandy basalt (boulder)	5-6.3	210.59	45.5	17.55	200	0.3
3	Sandy gravel	6.3-9	76.75	42.5	16.9	150	0.25
4	Clayey silt	9-13.3	150.76	27.5	16.36	15	0.3
5	Marl/shale	13.3-18.2	265	24.98	25.7	68000	0.24
6	Basaltic rocks	18.2-85	1214	52.51	31.59	76000	0.23

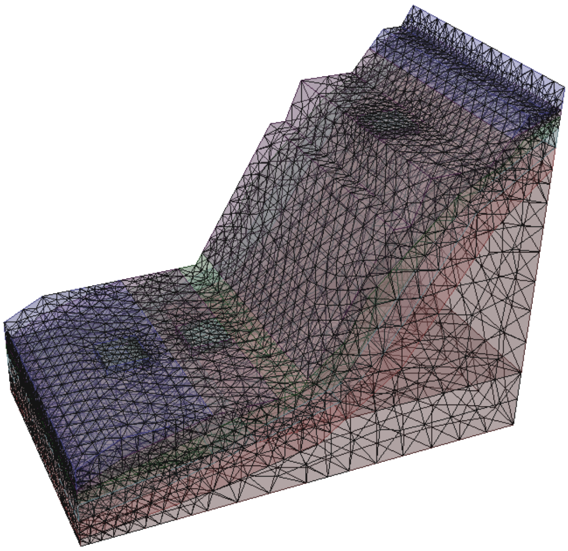
Boundary conditions: During FE modeling appropriate boundary conditions (i.e. both essential and natural) must be assigned to represent the actual problem accurately. This includes providing fixities, assigning flow boundary, surcharge loads, and prescribed displacements. In this study, the auto restraint (surface) restraint type was used. During static deformation analysis the model boundaries of the soil and rock were constrained in the x, y and z-direction.

Mesh generations: In this study, as shown in Table 4 and Figure 5, the 4-noded tetrahedral element was used. Generally, the accuracy of the solution is increased with decreasing element size and increasing the order of interpolation (i.e. quadratic is more accurate than linear). But the computation time increases with decreasing element size and increasing order of interpolation.

Table 4. Mesh properties and generations.

Element type	4-noded tetrahedral
Mesh gradation	Grade
Number of nodes	5794
Element numbers	26032

Figure 5. Meshing discretization of the model.

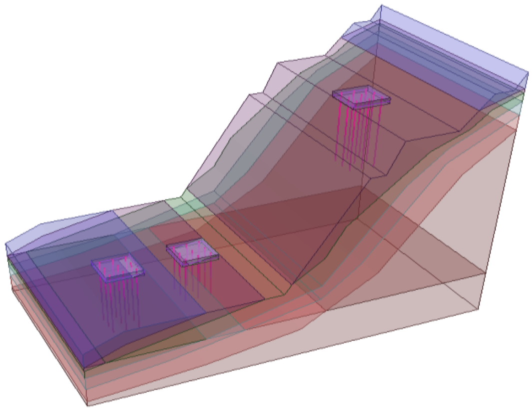


Support: The pile support was used to transfer the super structures Conveyor Belt load to the hard marl/shale and basaltic rocks. For this study, the pile properties were described in Table 5 and Figure 6.

Table 5. Properties of piles used in this study.

Properties	Units	Values
Pile elastic properties	Young's modulus (kPa)	3×10^7
	Poisson's ratio	0.2
Strength parameter	Area(m^2)	1.131
	I_{max}(m^4)	0.249
	I_{min}(m^4)	0.249
Geometry	Thickness(m)	1.2
	Length(m)	24.55 for CH1-12A
		17 for CH1-13A
		23.54 for CH1-14A
	Unit weight(kN/m^3)	25
Pile parameters	Shear stiffness(kPa)	10000
	Normal stiffness(kPa)	100000
	Base normal stiffness(kN/m)	100000
	Base force resistance(kN)	100
Skin resistance properties	Perimeter(m)	92.55 for CH1-12A
		64.09 for CH1-13A
		88.74 for CH1-14A
	Cohesion(kN/m)	57.74
	Residual cohesion(kN/m)	57.74
	Friction angle(deg)	29.64
	Residual friction angle(deg)	29.64

Figure 6. 3D Rock-socketed pile support.

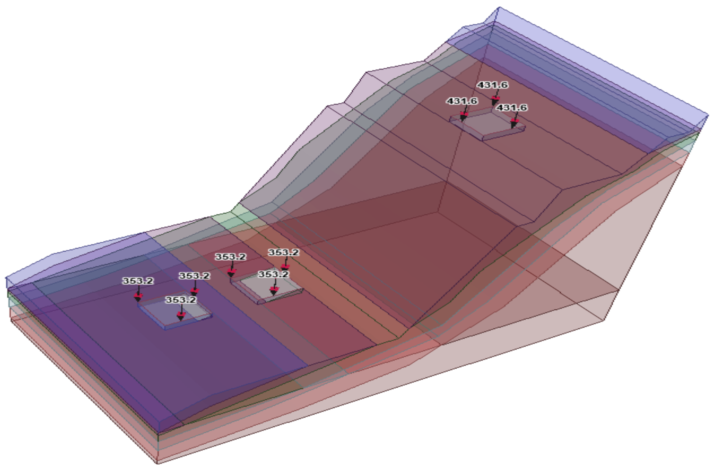


Loading: In modeling the gravity field stress type was used and the actual ground surface was considered during analysis. The load on the pile cap of the pile foundation was uniformly distributed loads as described in Table 6 and Figure7.

Table 6. Conveyor Belt load on the pile cap.

Column type	Load (kN/m²)
CH1-12A	431.64
CH1-13A	353.16
CH1-14A	353.16

Figure 7. 3D load of the actual ground surface during uniformly distributed loads.



Result of safety analysis using RS3 software

The safety factor of critical section was evaluated in 3D FEM (RS3 software) using shear strength reduction method. The evaluation was made for six static loading conditions (i.e. dry and initial condition, saturated and initial condition, saturated and Conveyor load condition, dry and Conveyor load, dry and Conveyor load with rock-socketed pile condition, saturated and Conveyor load with rock-socketed pile condition). The results of FS and stability of the slope for different static condition were showed (Table 7).

Table 7. Factor of Safety (FS) from RS3 software.

3D FEM (RS3 Software)	Dry and initial	Saturated and initial	Dry and conveyor load	Saturated and Conveyor load	Dry and Conveyor load with rock-socketed pile	Saturated and Conveyor load with rock-socketed pile
FS	3.763	1.401	3.761	1.92	3.698	1.648

Stability condition of the slope

As shown from the analysis result, at initial condition without raising of GWT and Conveyor load the FS equal to 3.763 was very safe. While FS is reduced up to 1.401 if GWT raises up to surface indicating that the slope will be greater than unity and stable. FS for Conveyor load without raising of GWT was equal to 3.761 also very safe and if GWT raise to ground surface with Conveyor load the FS is deducted to 1.92 still safe. At dry Conveyor load with rock-socketed pile condition FS is 3.698 very stable and if GWT at surface and Conveyor load with rock-socketed pile condition the FS reduced to 1.648 also stable.

Finally, the analysed results indicated that, even though the slope was stable, the stability of rock-socketed pile on inclined slope were highly depend on the GWT, so, the slope required the surface and subsurface drainage stabilizations to reduce the raising of GWT.

Stabilization mechanism of study area

In general, slope instability can be minimized by making adequate provisions to handle surface and subsurface water, by reducing the activating forces and by increasing the resisting forces. Generally, the selection of appropriate remedial measures depends on engineering feasibility, economic viability, and environmental acceptability. For this case, furrows and ditches were provided for surface drainage and horizontal and inclined drain pipe were provided to control subsurface drainage.

Pile foundation stability analysis using RSPile software

The stability of pile foundation for C1-12A, C1-13A and C1-14A were analysed by using 3D RSPile software and considered the vertical load, lateral load, dry and saturated condition. The analysis results were obtained in terms of displacement and lateral deflection as shown.

Similarly, for C1-13A, the maximum displacement in Y 1.91 mm and the maximum displacement in Z 1.33 mm was less than the maximum permissible displacement/settlement 10 mm. The maximum lateral deflections also less than the maximum permissible lateral deflection.

Similarly, for C1-14A, the maximum displacement in Y 1.2 mm and the maximum displacement in Z 1.11 mm was less than the maximum permissible displacement/settlement 10 mm. The maximum lateral deflections also less than the maximum permissible lateral deflection.

From hand calculations, for all C1-12A, C1-13A and C1-14A, the grouped pile was safe against uplift/pull-out failure. In general, the RSPile software and hand calculations result of pile foundation indicated that, the problem in the case study area was not the foundation failure problem.

CONCLUSIONS

The Conveyor Belt foundations of Dangote Cement founded on the natural inclined slope was faces frequent slope stability problems. Stability analyses of the slope was done to identify and analyse the critical slope section using different technique such as detailed field survey and numerical analysis. From field manifestations, the critical slope was identified. Laboratory test on representative sample taken from the field was conducted. Further stability analyses in terms of safety factor for both dry and saturated condition using FEM three-dimensional RS3 software was conducted. From field manifestations and numerical analyses, the following conclusions were made.

- In the investigated slope failure area, instability was triggered by the raising of water table in the rainy season due to infiltration of surface runoff.
- The Conveyor Belt loads applying additional forces on slope which plays great role in destabilizing of the slope and it was resisting by rock-socketed pile.
- The analysed results showed that, for saturated conveyor belt with rock-socketed pile, the factor of safety was 1.648 and it was stable.
- The factor of safety deducted from 3.698 for dry condition to 1.648 for saturated condition due to raising of ground water table.
- The stability analysis of rock-socketed pile on inclined slope was highly depending on the raising of ground water table.
- The maximum grouped pile settlement for C1-12A, C1-13A and C1-14A was less than the maximum permissible settlement.
- The maximum lateral deflection of grouped pile foundation less than the maximum permissible lateral deflection.
- Generally, the pile foundation was safe against bearing capacity, settlement, lateral deflection and uplift capacity failure.

In this study, the appropriate remedial measure was recommended based on the analyses result obtained from numerical analyses and the field visual manifestations, mainly the slopes were highly subjected to failure during the rainy season. In addition, poor drainage was maintained around slope instability area. Based on the identified slope stability governing factors, the following general remedial measure was recommended.

- Providing proper surface drainages (i.e. furrows and ditches) which can prevent infiltration of rainfall and flood into the slope.
- Providing the subsurface drainages (i.e. horizontal and inclined drain pipe) which reduce groundwater raise.

On the other hand, as the slope stability analysis was conducted within a limit scope, further study will be carried on the following;

- Performing 3D stability analysis using other commercial software such as PLAXIS (for FE analysis), FLAC 3D (for finite difference analysis) or any other commercial FE software's and 3D limit equilibrium methods.
- Considering additional factors such as: earthquake, vibrations and other dynamic conditions.

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