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Wedge Failure Analysis of the Slope Subjected to Uplift Forces by Analytical Method at Chingola Open Pits F & D

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Abstract

The influence of variable groundwater has been overlooked in the available literature. Yet, wedge failure induced by variable groundwater is still commonly experienced in sedimentary rock formation in many commercial dams, highways, and surface mine slopes around the world. In this article, a robust analytical model for stability analysis of the rock slopes subjected to wedge slope failure induced by variable groundwater is presented. This involves modifying the existing analytical model for estimating the safety factor of the rock slope subjected to wedge failure by incorporating the effects of variable groundwater. The proposed analytical model is validated using a numerical simulation model using the Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC3D) software. Furthermore, a real wedge slope instability at the Chingola Open-Pit Mine (COP F&D) induced by the presence of variable groundwater case history is studied in order to illustrate the effectiveness of the presented analytical model. The investigation results indicate that the presence of variable groundwater has a direct impact on the computed factor of safety of the rock slope subjected to wedge failure. The results obtained entail that the presented analytical model can provide a robust analytical model for the stability analyses of the rock slope subjected to wedge failure considering the presence of variable groundwater.

1. Introduction

One of the tasks performed by the mining and geotechnical engineers is to assess and maintain the stability of the natural or man-made slopes. Natural slopes usually remain stable when they are not disturbed by any dynamic forces (seismic, earthquakes, and blasting), surcharge loading, uplift forces due to groundwater, and rapid change in weather conditions. Slope failure is a critical hazard in open-pit mines, as it can be of any scale (small or large) and directly affects the people, equipment, and production processes. Therefore, analysis and calculation of slope stability are important for preventing the disasters that occur due to such instabilities [4-6]

Wedge failure is a type of slope failure that occurs due to sliding along a combination of discontinuities [3]. The wedge failure of rock slope is probably the most common type of failure in rock sliding [11].

It has been realized that wedge slope failure induced by the presence of groundwater is still common in the surface mining operations around the world. Wedge failure induced by groundwater becomes a nuisance to mine operations and worst a hazard. Groundwater is the common reason of slope instability. Thus it

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has received increasing attentions and has become a hot topic in the recent years. The failure of the slope under groundwater is a crucial issue for the slope stability subjected to wedge failure. Besides, very few scholars have conducted research works on wedge failure induced by groundwater using an analytical method on case studies. Yet, wedge failure induced by groundwater is still commonly experienced in sedimentary rock formation in many commercial dams, highways, and surface mine slopes around the world [1; 20]. In this paper, a case history of wedge slope instability at Chingola Open Pit Mine (COP F&D) induced by the presence of variable groundwater was studied. The presence of groundwater exerted negative influences on mining economics at COP F&D by creating risks for operational continuity and miners' safety, as well as having adverse environmental impacts. The percolation of water along fractures, joints, pores, faults, and cavities has resulted into physical and chemical actions on the pit walls of the mine. The principal stresses and the acting water pressure determine the stress state at a point in the rock mass. A discontinuity's shear strength is proportional to the applied normal stress. A drop in normal stress reduces the failure surface's shear strength. Additionally, the existing groundwater pressures might act as additional driving factors on failure surfaces. Hence, the need to research, study, and analyse the influence of uplift forces on the slope subjected to wedge failure at COP F&D. The research work conducted in this paper places emphasis on the wedge failure analysis of the mine slope subjected to uplift forces using an improved analytical model based on the limit equilibrium methods.

COP F&D is located along Chingola-Chililabombwe road on the Copperbelt Province in Zambia. It is approximately 71.9 km from Kitwe and 430 km from Lusaka. The location of COP F&D is shown on a map in Figure 1.

Figure 1. Location of COP F&D.

The rest of this paper is organized as wat follows. Literature reviews on wedge failure induced by groundwater and data collections for COP F&D are presented as a case study. Then the analytical model formulations for the wedge failure induced by the presence of groundwater based on the limit equilibrium are derived, and the parametric analysis considering variations of groundwater quantities is conducted. Thereafter, the results obtained are discussed in details. The conclusions and recommendations are arrived at based on the results. This research work provides additional literature on wedge failure induced by groundwater using an improved analytical method on case studies, and cushions the limited literature on this kind of failure mechanism.

Literature Review

Rock slope failure by wedge failure mechanism has been recognized worldwide by various researchers (John [17]; Hoek et al. [15];

Hockings [21], Cruden and Varnes [7], Wyllie and Mah [26]; Shukla et al. [23]).

Various factors that trigger wedge slope failure includes the physical and chemical properties of the rockmass, geometry of the slope, stress state, temperature, erosion, rainfall, seismicity as documented in the existing literatures by a number of researchers (Sharma et al. [22]; Yang and Zou [27]; Dahal et al. [8], Shukla et al. [23]; Hossain [12]; Kulatilake et al.[18] ; Ermias et al. [10], Hamza and Raghuvanshi [13]).

Groundwater exists almost everywhere beneath the surface of the earth. It is the water that fills the voids that exist in a rock mass. The water table is the surface that separates the saturated zone below, wherein all pore spaces are filled with water from the unsaturated zone above. Changes in the water table level occur due to changes in rainfall. During the wet seasons, the level of the water table tends to rise as more water infiltrates into the system, and falls during dry seasons as less water infiltrates into the system[15]. In mining the regions, groundwater is found in aquifers of various types including unconfined, semi-confined, and confined aquifers. The groundwater is kept either in the pore spaces of the rock or in the rock itself. It is intercepted when open mines are excavating minerals. A particular rock mass becomes weak when groundwater flows through fractures or discontinuities present in that bedrock, hence causing slope instability [3].

According to Fetter [11], groundwater is a critical factor that influences the stability of rock slope. Persistence dominates the extent of pre-existing potential failure surfaces. The force identified by Fetter [11]and Brehaut [4] is that of molecular attraction, which causes the water to adhere or bond to solid surfaces creating surface tension in the water when exposed to air. These are the fundamental contributing factors to wedge failure of the rock slope. The rock instabilities occur when a number of factors come together, and for one reason or another, the state of precarious stability prevailing until then passes an unstable situation resulting in rocks characterized by displacement [9; 14; 19] .

Furthermore, the existing groundwater pressures can act as additional driving forces on failure surfaces for certain failure modes. Secondary effects of having water present is that some minerals react unfavorably with water, thus reducing the material strength of a filled discontinuity for certain rock types. Erosion brought about by flowing water could also result in reduced strength [2; 16; 19; 24; 25]

2. Case history and material

A typical rock slope subjected to wedge failure that occurred due to the presence of ground water at the Chingola open-pit mine (COP.F) is shown in Figure 2.

The collected parameters from the mine site of the wedge block slope are summarized in Table 1.

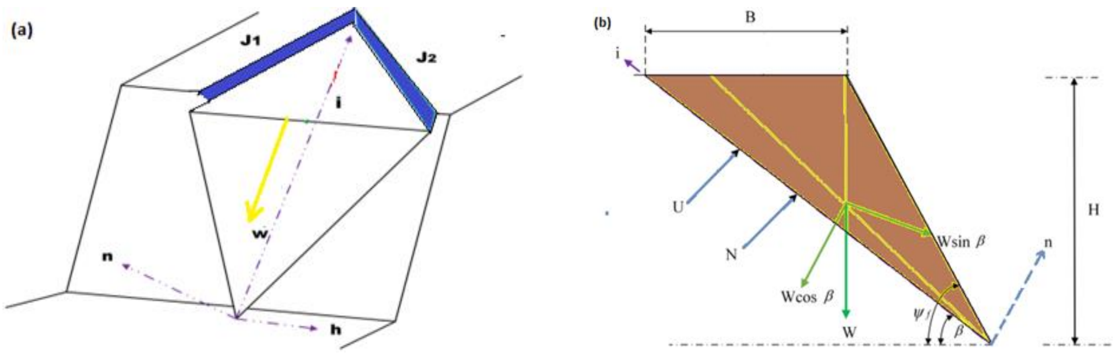
Figure 2. Wedge failure induced by presence of ground water at (COP F&D).

Table 1. Parameters of the wedge block and slope.

Description	Parameter
Bench height	15 m
Angle of slope	65°
Slope dip direction	60°
Dip and dip direction of joint plane $J_1(\theta_1)$	40°/130°
Dip and dip direction of joint plane $J_2(\theta_2)$	59°/211°
Failure surface angle	57°
Friction angle	30°
Volume	7743.975 m^3
Rock unit weight	2500 kN/m^3
Weight	19359.375 kN
Area of (joint 1)	150.339 m^2
Area of (joint 2)	126.158 m^2 $m2$
Area (slope face)	186.318 m^2
Area (upper face)	53.450 m^2
Normal force on (joint 1)	21.259 MPa
Normal stress on (joint 1)	0.141 MPa
Normal force on (joint 2)	17.957 MPa
Normal stress on (joint 2)	0.142 MPa
Cohesion	226 kPa

3. Analytical formulation

From the presented data in Table 1, it is assumed that the particular wedge selected is not subjected to surcharge load and any seismic activities such as earthquakes and blasting. The wedge failure only occurred due to the presence of variable groundwater forces (U), the slope geometry, and the weight of the wedge block (W). Conceptual three dimension (3D) geometrical view of the wedge failure induced by the presence of groundwater at (COP F&D) is shown in Figure 3. Figure 3(a) is a 3D view of wedge showing the intersection lines and planes, while Figure 3(b) is a vertical plane view, and Figure 3(c) shows the transverse section to i direction.



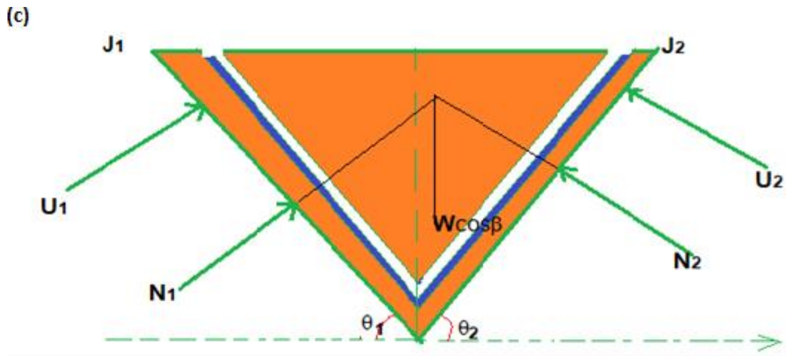


Figure 3. 3D geometrical view of the particular wedge blocks being analyzed.

Factor of safety (FOS) is expressed as:

$$\mathrm{FOS} = \frac{\mathrm{F_{resist}}}{\mathrm{F_{drive}}} \quad (1)$$

where:

$\mathrm{F_{resist}}$ is the global forces present to resist slope failure

$\mathrm{F_{drive}}$ is the global forces present to induce slope failure

$$\mathrm{F_{resist}} = \tau . A \quad (2)$$

where τ = shear strengths

A = Base area of the sliding block

$$\tau = cA + (N_1 + N_2)tan\emptyset \quad (3)$$

where $C = cohesion$

N_1 = Normal forces applied on joint plane (j_1)

N_2 = Normal force applied on joint plane (j_2)

$$N_1 = \frac{wcosbsin\theta_2}{sin(\theta_1 + \theta_2)} \quad (4)$$

$$N_2 = \frac{wcosbsin\theta_1}{sin(\theta_1 + \theta_2)} \quad (5)$$

where w = weight of block.

By replacing Equation 3 into Equation 2, we obtain:

$$\mathrm{F_{resist}} = \left(c + (N_1 - U_1)tan\emptyset_{j_1} + (N_2 - U_2)tan\emptyset_{j_1}\right)A$$
$$= (N_1 - U_1)tan\emptyset_{j_1} + (N_2 - U_2)tan\emptyset_{j_1} + c_1.j_1 + c_2.j_2 \quad (6)$$

Since

$$F_{\mathrm{drive}} = wsin\beta \quad (7)$$

we can deduce another expression for the factor of safety by substituting Equations 6 and 7 into Equation 1 to form Equation 8.

$$\mathrm{FOS} = \frac{(N_1 - U_1)tan\emptyset_{j_1} + (N_2 - U_2)tan\emptyset_{j_1} + c_1.j_1 + c_2.j_2}{wsin\beta} \quad (8)$$

Where

U_1 = uplift force on joint 1

U_2 = Uplift force on joint 2

The weight (W) of the wedge block is resolved using Equation 9.

$$W = \gamma V = \gamma H\frac{B}{6} \quad (9)$$

The uplift forces due to groundwater pressure along joints are resolved using Equation 10.

$$U = U_1 + U_2 = \frac{\gamma_w B}{6}A_U + \frac{\gamma_w H}{6}A_U$$
$$= \frac{\gamma_w H}{3}A_U \quad (10)$$

where γ_w = Unit weight of water

$$A_U = \frac{BH}{2} \quad (11)$$

The factor of safety is further resolved by substituting Equations 4, 5, 9, 10, and 11 into Equation 8 to obtain Equation 12.

$$FOS = \frac{(N_1 - U_1)tan\emptyset_{j_1} + (N_2 - U_2)tan\emptyset_{j_1} + c_1.j_1 + c_2.j_2}{wsin\beta}$$

$$FOS = \frac{\left(\frac{wcosbsin\theta_2}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6}A_U\right)tan\emptyset_{j_1} + \left(\frac{wcosbsin\theta_1}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6}A_U\right)tan\emptyset_{j_1} + c_1.j_1 + c_2.j_2}{wsin\beta}$$

$$FOS = \frac{\left(\frac{\gamma H\frac{B}{6}cosbsin\theta_2}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6}\frac{BH}{2}\right)tan\emptyset_{j_1} + \left(\frac{\gamma H\frac{B}{6}cosbsin\theta_1}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6}\frac{BH}{2}\right)tan\emptyset_{j_1} + c_1.j_1 + c_2.j_2}{\gamma H\frac{B}{6}sin\beta} \quad (12)$$

$$FOS = \frac{\left(\frac{\gamma H\frac{B}{6}cosbsin\theta_2}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6}\frac{BH}{2}\right)tan\emptyset_{j_1} + \left(\frac{\gamma H\frac{B}{6}cosbsin\theta_1}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6}\frac{BH}{2}\right)tan\emptyset_{j_1} + c_1^*.j_1 + c_2^*.j_2}{\gamma H\frac{B}{6}sin\beta}$$

Where $c_1^* = \frac{c_1}{\gamma H}$ and $c_2^* = \frac{c_2}{\gamma H}$

If the joint planes are both smooth, the cohesion is resolved using Equation 13.

$$c_1^* = c_2^* = 0 \quad (13)$$

By substituting Equation 13 into Equation 12, the factor of safety is deduced to Equation 14.

$$FOS = \frac{\left(\frac{\gamma H\frac{B}{6}cosbsin\theta_2}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6}\frac{BH}{2}\right)tan\emptyset_{j_1} + \left(\frac{\gamma H\frac{B}{6}cosbsin\theta_1}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6}\frac{BH}{2}\right)tan\emptyset_{j_1}}{\gamma H\frac{B}{6}sin\beta} \quad (14)$$

For varying values of uplift forces, Equation 14 derived below will be used to determine the factor of safety.

We know that:

$$U = U_1 + U_2 = \frac{\gamma_w B}{6}A_U + \frac{\gamma_w H}{6}A_U = \frac{\gamma_w H}{3}A_U$$

and:

$$A_U = \frac{BH}{2}$$

Therefore,

$$U = \frac{\gamma_w H}{3}\frac{BH}{2} = \frac{(\gamma_w H)BH}{6} \quad (15)$$

Substituting Equation 14 into Equation 12, we obtain Equation 16.

$$FOS = \frac{\left(\frac{\gamma H\frac{B}{6}cosbsin\theta_2}{sin(\theta_1+\theta_2)} - \frac{U}{2}\right)tan\emptyset_{j_1} + \left(\frac{\gamma H\frac{B}{6}cosbsin\theta_1}{sin(\theta_1+\theta_2)} - \frac{U}{2}\right)tan\emptyset_{j_1} + c_1^*.j_1 + c_2^*.j_2}{\gamma H\frac{B}{6}sin\beta} \quad (16)$$

3.1. Parametric analyses

In order to examine the wedge sliding on the slope, a 3D model of the block was depicted to clearly describe the particular region selected. For analysis, the factor of safety was derived to incorporate uplift forces. The rock unit weight and volume were taken as 2500 kN/ and 7743.975 , respectively (see Table 1). From the magnitude of the unit weight and volume, the weight of the wedge block was calculated as 19,359.94 kN. The variations in magnitudes of uplift forces are provided in Table 2. Parametric analyses are conducted using the weight, cohesion, bench height, and slope angle; angle of friction and variations in magnitudes of uplift forces are provided to determine the factor of safety. The results obtained are plotted in Figure 4 below. This figure shows the graph for the factor of safety plotted against variations in the uplift forces. Table 2 shows the ranging values of the safety factor for varying magnitudes of uplift forces.

Table 2. Safety factor for varying magnitudes of uplift forces.

Uplift force U (kN/m^3)	Factor of safety (FoS)
2.3	1.34
2.6	1.31
2.9	1.28
3.1	1.26
3.4	1.23
3.7	1.20
4.0	1.17

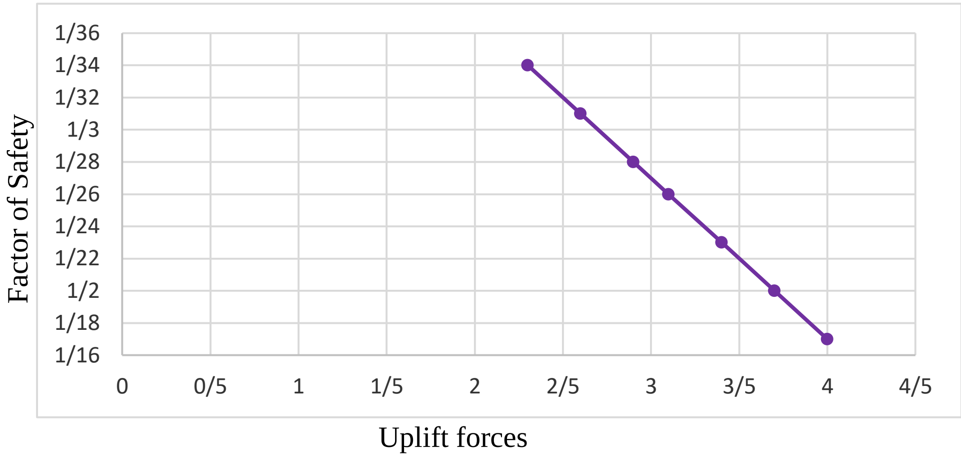


Figure 4. Graph of safety factor plotted against uplift forces.

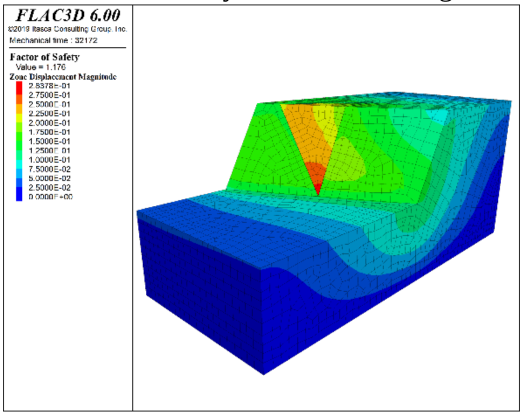
3.2. Verifications

In this work, the numerical simulation model using FLAC 3D was applied to validate the proposed analytical model. Investigations of the physical slope failure rarely provide precise understandings into the fundamental failure mechanisms and stability of the slope. Accurate insights of physical slope study are usually masked by geometry, geological complexities, and debris. Hence, an accurate numerical model is a smart substitute for validating the accuracy of analytical models for examining the stability of slope failure. FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) is the numerical modeling software for geotechnical analyses of soil, rock, groundwater, constructs, and ground support. Such analyses include engineering design, factor of safety prediction, research and testing, and back-analysis of failure. FLAC3D utilizes an explicit finite volume formulation that captures the complex behaviors of the models that consist of several stages, showing large displacements and strains, exhibit non-linear material behavior or are unstable (including cases of yield/failure over large areas or total collapse).

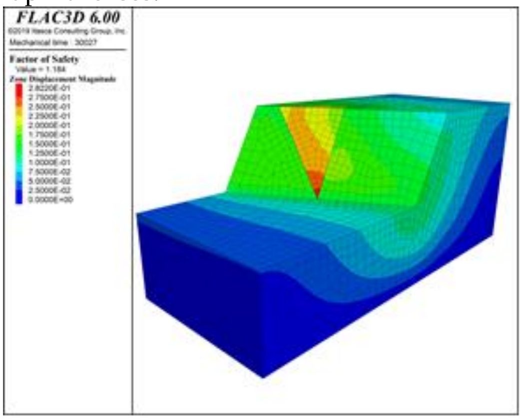
In this work, Fine numerical simulation using Fast Lagrangian Analysis of Continua in 3 Dimensions software (FLAC3D) using the same combinations of mechanical properties and the same geological properties (analytical model) is used in the case history. A variety of numerical models but with variation of uplift forces (Table 2) were applied to simulate the evolution process of the physical behaviour, and the resulting factor of safety of the rock slope is subjected to wedge failure. Figure 5 (a-g) below shows the evolution process of the physical behaviour, and the resulting factor of safety of the rock slope is subjected to wedge failure considering the variations in groundwater in a rock slope.

3.3. Comparative analyses

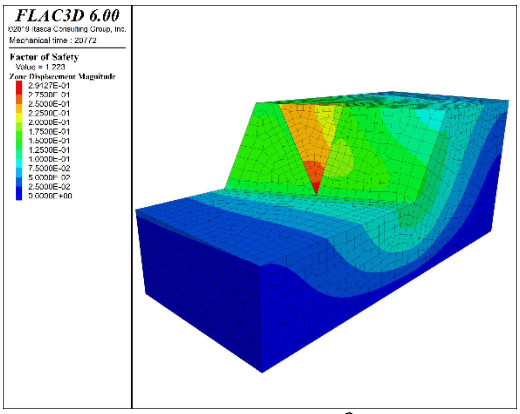
A comparative slope stability analysis between an improved analytical and numerical simulation models was conducted on the same real rock slope susceptible to wedge failure mechanisms. The aim was to investigate the resulting factor of safety subjected to variations in groundwater. The factor of safety results obtained by the improved analytical models were investigated to establish if it aligns well with the factor of safety obtained by the numerical simulation models. This was conducted to confirm the validity of the improved analytical model for stability analysis of the jointed rock slopes subjected to wedge failure under varying groundwater. The comparative results are summarized in Table 3 below. The factor of safety obtained using the proposed analytical method is consistent with the factor of safety obtained using the numerical model by FLAC3D. This confirms the validity of the proposed analytical model. The minor differences (negligible) in the resulting FoS obtained by both methods that exists is attributed to estimations by the analytical model unlike the numerical simulation model. Moreover, the simulation results obtained by numerical models on a rock slope demonstrated that the progressive displacements were intensified with increasing uplift forces.



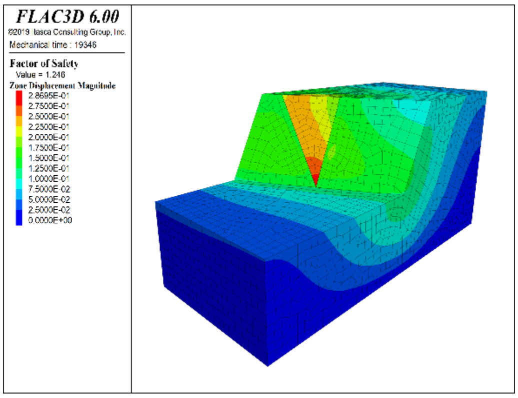
(a): U = 2.3 (kN/m^3)



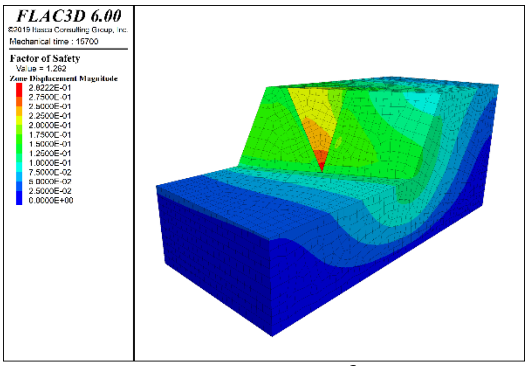
(b): U = 2.6 (kN/m^3)



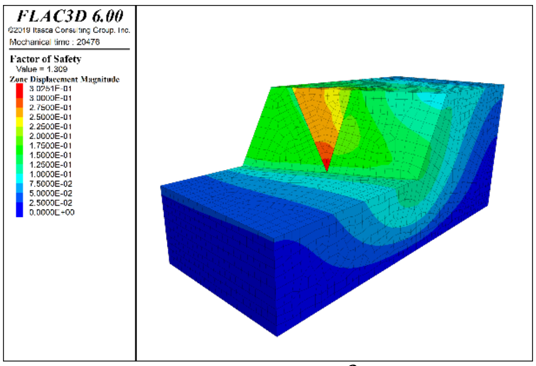
(c): U = 2.9 (kN/m^3)



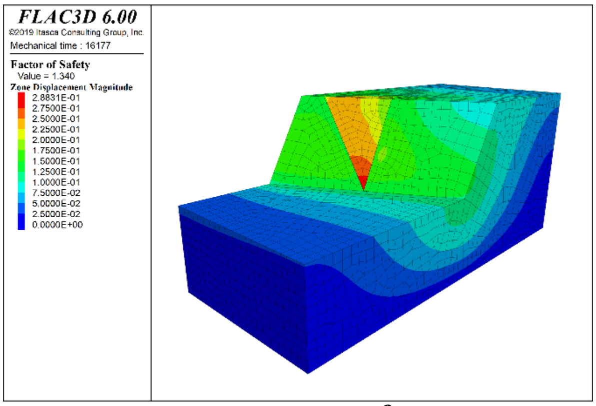
(d): U = 3.1 (kN/m^3)



(e): U = 3.4 (kN/m^3)



(f): U= 3.7 (kN/m^3)



(g): U = 4.0 (kN/m^3)

Figure 5. Results of numerical simulation model of a rock slope subjected to edge failure mechanisms under variations of uplift forces.

Table 3. Safety factor obtained by analytical and numerical models under varying magnitudes of uplift forces.

Uplift force U (kN/m^3)	FoS by analytical model	FoS by numerical model
2.3	1.34	1.340
2.6	1.31	1.309
2.9	1.28	2.282
3.1	1.26	2.262
3.4	1.23	1.228
3.7	1.20	1.184
4.0	1.17	1.176

4. Results and discussion

The wedge sliding analysis using the parameters and conditions presented in Table 1 provided the FOS results presented in Tables 2 and 3. The calculated factor of safety presented in Tables 2 and 3 entail that as the uplift force acting along the joint planes increases due to an increase in the water pressure, there is a significant decrease in the resulting safety factor. As the uplift force acting along the joint planes is reducing due to a reduction in the water pressure, there is a significant increase in the resulting safety factor of the slope.

From Tables 2 and 3, it can be noted that after the magnitude of the uplift force increased from 2.3 to 2.6, the factor of safety also reduced from 11.340 to 1.1.309 proportionally. As the magnitude of the uplift forces was further increased to 4.0, a significant decrease in the safety factor was recorded as 1.176, showing the continuing trend. From these results, it can be deduced that as the magnitude of the uplift forces increases, the safety factor decreases. In other words, the magnitude of the uplift forces is inversely proportional to the value of the safety factor. Another factor that decreased the factor of safety was the weight of the wedge block. The heavier the block, the less factor of safety recorded and higher chances of wedge failure. The data obtained in Table 2 was then plotted on a graph of factor of safety against uplift forces, as shown in Figure 4. From the graph, it can be noticed that as the magnitudes of uplift forces began to increase, the factor of safety started reducing, showing a downward trend. If the factor of safety was to be increased, the magnitude of the uplift forces was to be reduced.

From Figure 4 and Tables 2 and 3, it can be deduced that in order to have an improved factor of safety, the magnitude of the uplift forces should be significantly reduced. This is achieved through installation of depressurization points or inclined drain holes through the face of the slope to drain out water.

5. Conclusions

In the current work, we proposed an analytical model for estimating the safety factor for rocky slopes when wedge failure of the slope was triggered by the uplift forces operating along the joint planes due to water pressure, based on the results and discussions given. The effects of differences in the uplift forces operating along the joint planes on the safety factor of the slope subjected to wedge sliding were investigated in a detailed parametric study. The major causes of the wedge's instability were determined to be gravity-induced water pressure. When wedge sliding occurs at relatively modest uplift forces operating along the joint planes, a slope proclaimed stable can become dangerous, as the uplift forces acting along the joint planes increase. The intensity of rise in the uplift forces operating along the joint planes owing to water pressure can cause a rapid deterioration in the stability of the rock slope prone to wedge sliding. Within a rock mass, the wedge-shaped pieces of rock surrounded by two discontinuities represent an important sort of danger. When compared to the hazards with a single prominent discontinuity, these hazards are more difficult to spot.

5.1. Recommendation

The magnitude of the uplift forces should be kept to a minimum in order to obtain a favorable factor of safety. The presence of groundwater pressure causes uplift forces in the ground. As a result, by installing powerful dewatering systems to pump out the water, the water pressure is reduced. Thus the amplitude of the uplift forces is reduced.

References

[1]. Bowa, V.M. (2019). Wedge Sliding Analysis of the Rock Slope Subjected to Uplift Forces and Surcharge Loads Conditions. Geotechnical and Geological Engineering. 38 (1): 367–374. https://doi.org/10.1007/s10706-019-01027-4

[2]. Bowa, V. M. a. G., W. (2021). Analytical technique for stability analyses of the rock slope subjected to slide head toppling failure mechanisms considering groundwater and stabilization effects. International Journal of Geo-Engineering. 12 (1).

[3]. Bowa, V.M.a.K.,T. (2020). Wedge Failure Analyses of the Jointed Rock Slope Influenced by Foliations. Geotechnical and Geological Engineering. 38 (5): 4701–4710.

[4]. Brehaut, R.J. (2009). Groundwater, Pore Pressure and Wall Slope Stability–a model for quantifying pore pressures in current and future mines.

[5]. Bui, X.-N., Nguyen, H., Choi, Y., Nguyen-Thoi, T., Zhou, J. and Dou, J. (2020). Prediction of slope failure in open-pit mines using a novel hybrid artificial intelligence model based on decision tree and evolution algorithm. Scientific Reports. 10 (1).

[6]. Chang, Y., Lin, C. and Lin, M. (2021). Influences of Joint Persistence and Groundwater on Wedge Failure Potential of Jointed Rock Slope, 7303.

[7]. Cruden , D.M.a.V., D.J. (1996). Landslide types and processes. In: Turner K, Schuster RL (Eds) Landslides: investigation and mitigation.

[8]. Dahal, R.K., Hasegawa, S., Masuda. T., and Yamanaka, M. (2006). Roadside slope failures in Nepal during torrential rainfall and their mitigation. In: Marui et al. (Eds) Disaster mitigation of debris flows, slope failures and landslides.

[9]. Doumbouya, L., Guan, C.S. and Bowa, V.M. (2019). Influence of Rainfall Patterns on the Slope Stability of the Lumwana (the Malundwe) Open Pit. Geotechnical and Geological Engineering. 38 (2): 1337–1346.

[10]. ERMIAS, B., RAGHUVANSHI, T.K. and ABEBE, B. (2017). Landslide Hazard Zonation (LHZ) Around Alemketema Town, North Showa Zone, Central Ethiopia - A GIS Based Expert Evaluation Approach. International Journal of Earth Sciences and Engineering. 10 (01): 33–44.

[11]. Fetter, G. (1994). Preparation and Characterization of Montmorillonites Pillared by Cationic Silicon Species. Clays and Clay Minerals. 42 (2): 161–169.

[12]. Ganjeh, R.S., Memarian, H., Khosravi, M., and Mojarab, M. (2019). A comparison between effects of earthquake and blasting on stability of mine slopes: a case study of Chadormalu open-pit mine. Journal of Mining and Environment. 10 (1): 223–240. https://doi.org/10.22044/jme.2019.7535.1607.

[13]. Hamza, T.a.R., T.K. (2017). GIS based landslide hazard evaluation and zonation – A case from Jeldu District, Central Ethiopia. Journal of King Saud University – Science. 29 (2): 151–165.

[14]. Hoek, E. (1971, November 1971). Recent Rock Slope Stability Research at the Royal School of Mines. 2nd International Conference on Stability in Open Pit Mining, Vancouver.

[15]. Hoek, E. (2009). Fundamentals of slope design. Keynote address at slope stability 2009, Santiago, Chile.

[16]. Huang, S., Lv, Y., Peng, Y., Zhang, L., and Xiu, L. (2015). Effect of different groundwater levels on seismic dynamic response and failure mode of sandy slope. PLoS ONE. 10 (11): 1–11. https://doi.org/10.1371/journal.pone.0142268.

[17]. John, K.W. (1970). Engineering analysis of three dimensional stability problems utilizing the reference hemisphere. 2nd international congress of

international society on rock mechanics. 2 (1): 314–321.

[18]. Kulatilake, P.H.S.W., Wang, L., Tang, H. and Liang, Y. (2011). Evaluation of rock slope stability for Yujian River dam site by kinematic and block theory analyses. Computers and Geotechnics. 38 (6): 846–860.

[19]. Kumsar, H., Aydan and Ulusay, R. (2000). Dynamic and Static Stability Assessment of Rock Slopes Against Wedge Failures. Rock Mechanics and Rock Engineering. 33 (1): 31–51.

[20]. Nelson, S.A. (2013). Slope Stability, Triggering Events, Mass Movement Hazards. EENS 3050 Natural Disasters Tulane University.

[21]. Razdolsky, A.G. (2008). Slope stability analysis based on the direct comparison of driving forces and resisting forces. International Journal for Numerical and Analytical Methods in Geomechanics. 33 (8): 1123–1134.

[22]. Sharma, S., Raghuvanshi,T., Anbalagan, R. (1995). Plane failure analysis of rock slopes. Geotech Geol Eng 13, 105–111.

[23]. Shukla, S.K. a. H., Md.M. (2011). Stability analysis of multi-directional anchored rock slope subjected to surcharge and seismic loads. Soil Dynamics and Earthquake Engineering. 31 (5-6): 841–844.
https://pdfs.semanticscholar.org/0039/3e27712749b12f5bf8ab9333dde3802f5318.pdf

[24]. Smith, J.V. a. A., C. (2016). Distinguishing between single and double plane sliding of tetrahedral wedges using the circle method. Engineering Geology, 211, 98–101.

[25]. Wang, Y.J., Yin, J.H., Chen, Z., and Lee, C.F. (2004). Analysis of wedge stability using different methods. Rock Mechanics and Rock Engineering. 37 (2): 27–150.

[26]. Wyllie, D.C. a. M., C.W. (2004). Rock Slope Engineering, Civil and Mining. (Fourth Edition, ed.). SPON Press.

[27]. Yang, X. L. a. Z., J.F. (2006). Stability factors for rock slopes subjected to pore water pressure based on the Hoek–Brown failure criterion. Int J Rock Mech Min Sci 43 (7): 1146–1152.

تجزیه و تحلیل شکست گوه‌ای شیب تحت نیروهای بالابرنده با روش تحلیلی در معدن روباز چینگولا F & D

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چکیده:

تأثیر وجود پارامتر آب‌های زیرزمینی در تحقیقات پیشین نادیده گرفته شده است. هنوز هم شکست گوه‌ای القا شده از وجود آب‌های زیرزمنی در سنگ‌های رسوبی در دیواره‌های سدها، بزرگراه‌ها و پله‌های معدنی اتفاق می‌افتد. در این مقاله، یک مدل تحلیلی قوی برای تحلیل پایداری شیب‌های سنگی در معرض شکست گوه ناشی از آب‌های زیرزمینی ارائه شده است. این کار شامل اصلاح مدل تحلیلی موجود برای تخمین ضریب ایمنی دیواره‌های سنگی که در معرض شکست گوه‌ای ناشی از اثرات وجود آب‌های زیرزمینی است انجام شده است. مدل تحلیلی پیشنهادی با استفاده از یک مدل شبیه‌سازی عددی با استفاده از نرم‌افزار سه بعدی (FLAC3D) اعتبارسنجی شده است. علاوه بر این، یک ناپایداری گوه‌ای واقعی در معدن روباز Chingola (COP F&D) ناشی از حضور آب زیرزمینی به منظور نشان دادن اثربخشی مدل تحلیلی ارائه‌شده، مورد مطالعه قرار گرفت. نتایج بررسی نشان می‌دهد که وجود آب زیرزمینی تأثیر مستقیمی بر ضریب ایمنی محاسبه‌شده شیب سنگی که در معرض شکست گوه‌ای قرار دارد، می‌شود. نتایج به‌دست‌آمده مستلزم آن است که مدل تحلیلی ارائه‌شده می‌تواند یک مدل تحلیلی قوی برای تحلیل‌های پایداری شیب سنگی در معرض شکست گوه‌ای ناشی از وجود آب‌های زیرزمینی ارائه دهد.

کلمات کلیدی: شکست گوه‌ای، سنگ درزه‌دار، آب زیرزمینی، مدل تحلیلی، ضریب اطمینان.