2023 ENGINEERING INSTITUTION OF ZAMBIA SYMPOSIUM

Wedge failure analysis of a slope subjected to uplift forces by analytical method

PRESENTER : Mwango Bowa

DATE : Friday 19th April 2024

Avani Victoria Falls Resort, Livingstone, Zambia

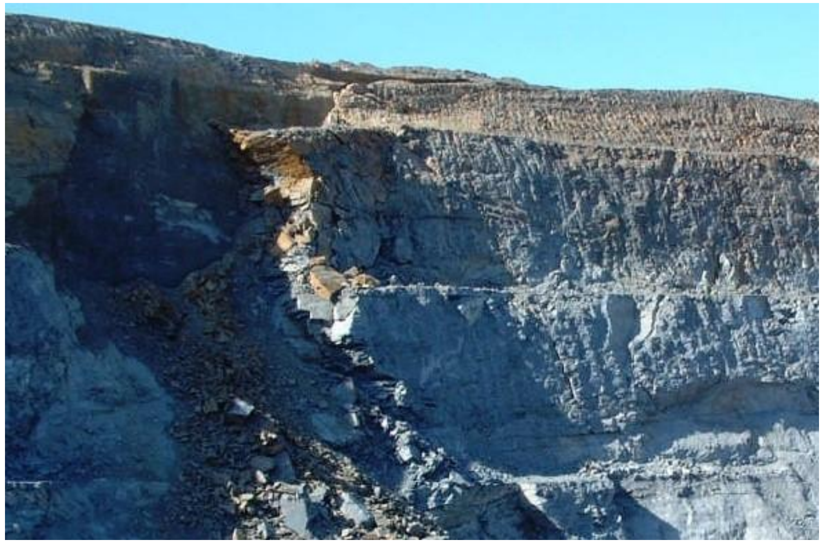
Table of Content

Introduction

- The influence of groundwater on wedge slope stability has been overlooked in the available literature.
- Yet, wedge failure induced by groundwater is still commonly experienced in many surface mine slopes around the world..

Wedge failure at COF&D- Zambia- Bowa and Kasanda 2020

Wedge failure at Kargoorlie mine- Australia- Makarov et al. 2022



Wedge failure at Round Hill Open Pit- New Zealand (Brown I 1996)

Cont’d

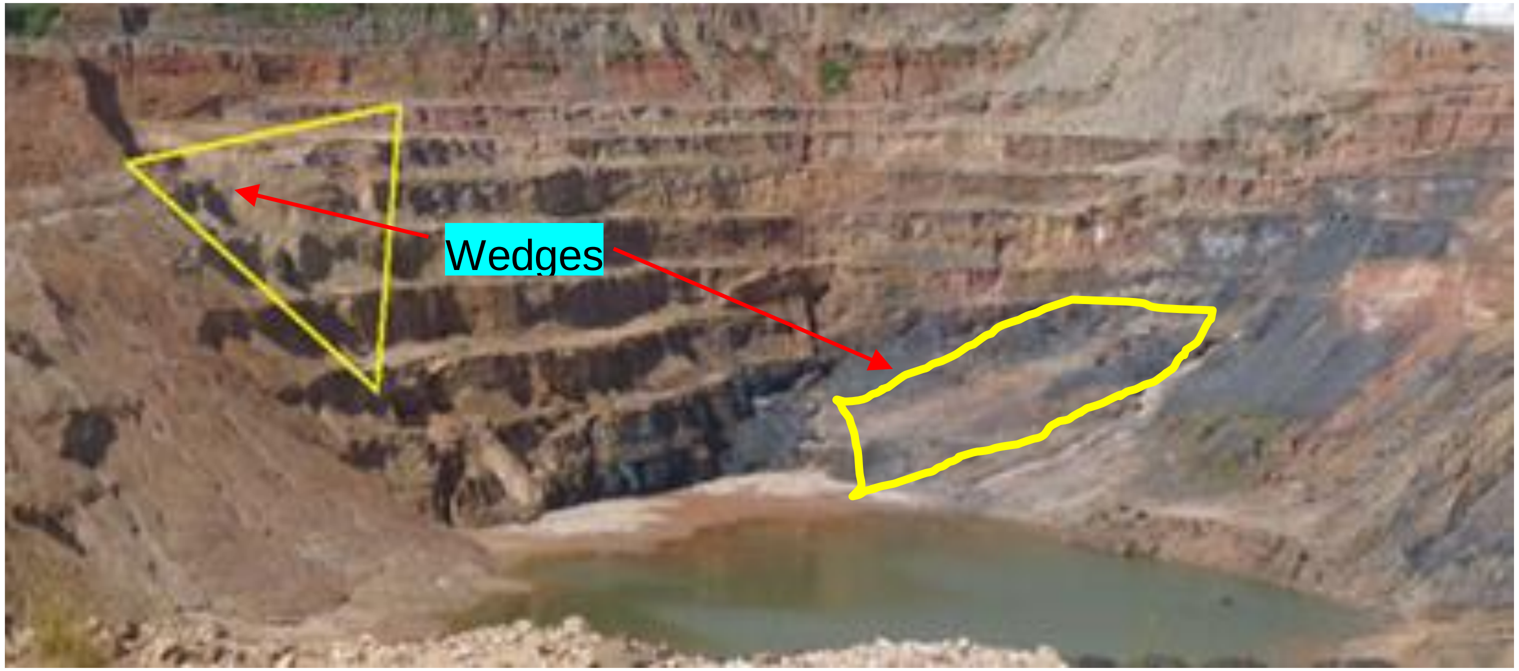
- However, the influence of **uplift forces** in **inducing wedge slope failure has received limited attention** in the available literature.
- In our article a robust analytical model for stability analysis of the rock slopes subjected to wedge slope failure induced by variable groundwater is presented.
- The proposed analytical model was validated using a numerical simulation model using a 3D software (FLAC3D).

Cont'd

- Furthermore, a real wedge slope instability at Chingola Open Pits F and D (COP F&D) induced by the presence of groundwater was studied to illustrate the effectiveness of the presented analytical model.
- The investigation results indicate that the presence of groundwater has impact on the computed Factor of Safety (FoS) of the slope subjected to wedge failure.
- The study results entail that the presented analytical model can provide a robust analytical model for stability analysis of a slope subjected to wedge failure considering the presence of groundwater.

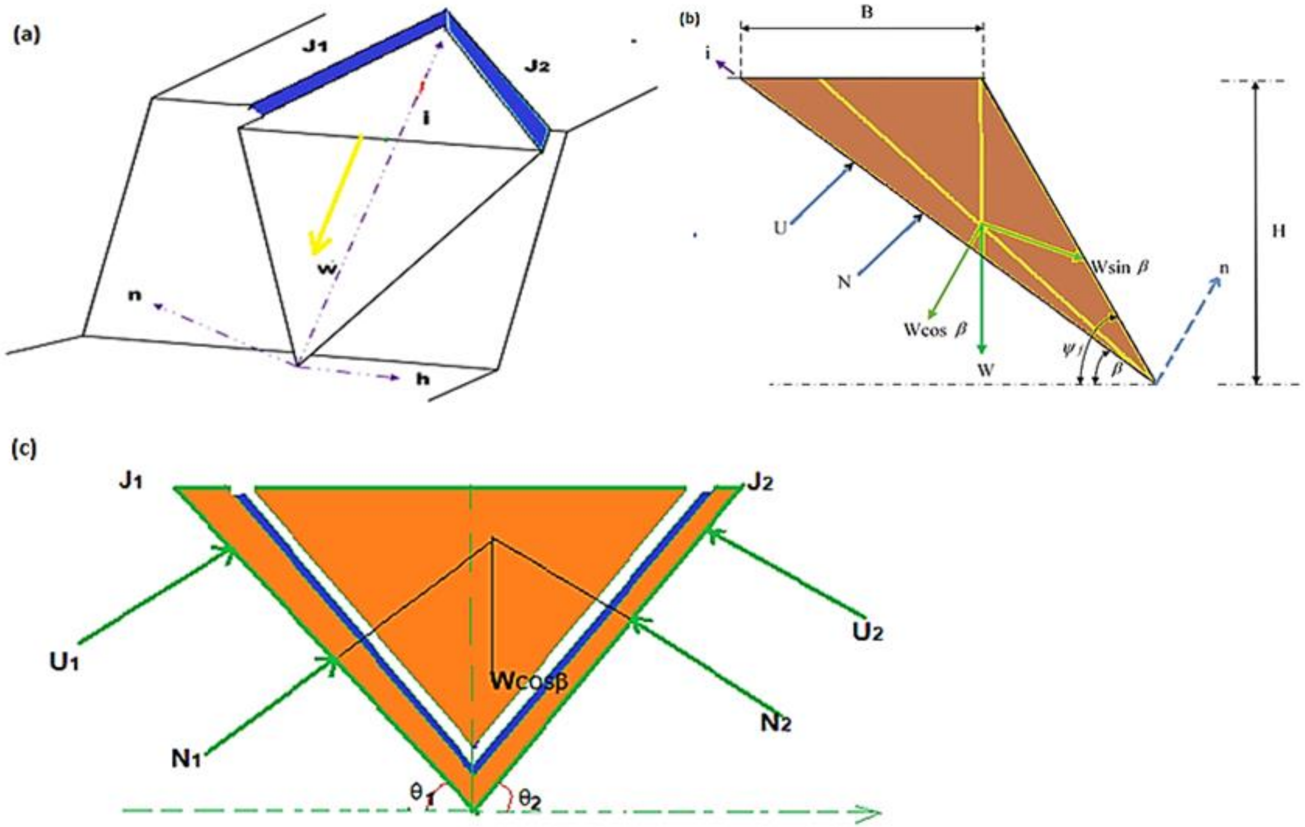
A case history

- A typical rock slope subjected to wedge failure that occurred allegedly triggered by the presence of groundwater at COP F & D is shown in the picture below.



Wedge failure induced by the presence of groundwater at (COP F&D).

Conceptual models for stability analysis



a) 3D view of wedge showing the intersection lines and planes, b) view vertical plane view, c) showing transverse section to *i* direction.

Analytical Formulation

- Factor of Safety, FoS = $\frac{Restraining\ forces}{Activating\ forces}$ …. (1)
- $\text{RestrF}_{\text{resist}} = \tau . A$ (2)

Where τ = shear strengths

A = base area of the sliding block

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

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

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

Cont'd

By replacing Equation 3 into Equation 2 we obtain

- $\mathrm{F}_{\mathrm{resist}} = \left(c + (N_1 - U_1)tan\emptyset_{j_1} + (N_2 - U_2)tan\emptyset_{j_1}\right)A$

$= (N_1 - U_1)tan\emptyset_{j_1} + (N_2 - U_2)tan\emptyset_{j_1} + c_1.j_1 + c_2.j_2$ (6)

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

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

Where $U_1 =$ uplift force on joint 1 and $U_2 =$Uplift force on joint 2

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

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

Cont’d

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

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

Where γ_w =unit weight of water

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

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

- $\text{FoS} = \frac{(N_1 - U_1)tan\emptyset_{j_1} + (N_2 - U_2)tan\emptyset_{j_1} + c_1.j_1 + c_2.j_2}{wsin\beta}$
- $\text{FoS} = \frac{\left(\frac{wcosbsin\theta_2}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6} A_U\right)tan\emptyset_{j_1} + \left(\frac{wcosbsin\theta_1}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6} A_U\right)tan\emptyset_{j_1} + c_1.j_1 + c_2.j_2}{wsin\beta}$
- $\text{FoS} = \frac{\left(\frac{\gamma H \frac{B}{6} cosbsin\theta_2}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6}\frac{BH}{2}\right)tan\emptyset_{j_1} + \left(\frac{\gamma H \frac{B}{6} cosbsin\theta_1}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6}\frac{BH}{2}\right)tan\emptyset_{j_1} + c_1.j_1 + c_2.j_2}{\gamma H \frac{B}{6} sin\beta}$
- $\text{FoS} = \frac{\left(\frac{\gamma H \frac{B}{6} cosbsin\theta_2}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6}\frac{BH}{2}\right)tan\emptyset_{j_1} + \left(\frac{\gamma H \frac{B}{6} cosbsin\theta_1}{sin(\theta_1+\theta_2)} - \frac{\gamma_w H}{6}\frac{BH}{2}\right)tan\emptyset_{j_1} + c_1^*.j_1 + c_2^*.j_2}{\gamma H \frac{B}{6} sin\beta}$ (12)

Cont’d

Where $c_1^* = \frac{c_1}{\gamma H}$ and $c_2^* = \frac{c_2}{\gamma H}$ If the joint planes are both not rough, the cohesion is resolved using Equation 13.

- $c_1^* = c_2^* = 0$ (13)

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

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

For varying values of uplift forces, Equation 14 derived below will be used to determine the factor of safety.$U = U_1 + U_2 = \frac{\gamma_w B}{6} A_U + \frac{\gamma_w H}{6} A_U = \frac{\gamma_w H}{3} A_U$

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

Substituting Equation 14 into Equation 12 we obtain Equation 16

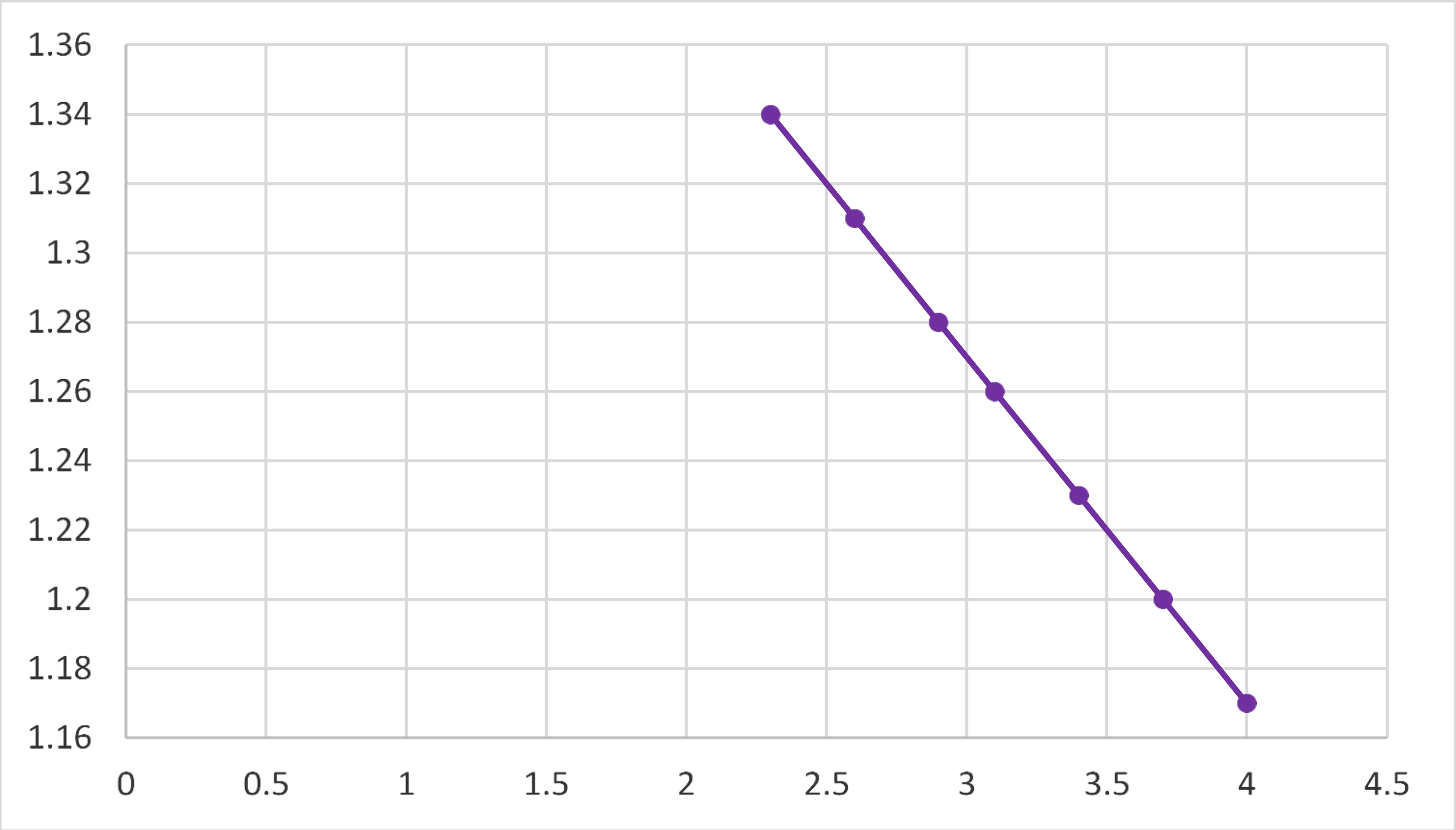
- $\text{FoS} = \frac{\left(\frac{\gamma H \frac{B}{6} cosbsin\theta_2}{sin(\theta_1+\theta_2)} - \frac{U}{2}\right) tan\emptyset_{j_1} + \left(\frac{\gamma H \frac{B}{6} cosbsin\theta_1}{sin(\theta_1+\theta_2)} - \frac{U}{2}\right) tan\emptyset_{j_1} + c_1^*.j_1 + c_2^*.j_2}{\gamma H \frac{B}{6} sin\beta}$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

Parametric analyses

- In order to examine the wedge sliding on the slope (FoS), a 3D model of the block was depicted to clearly describe the particular region selected.
- Parametric analyses were conducted using the weight, cohesion, bench height, and slope angle; angle of friction and variations in magnitudes of uplift forces are provided

Results

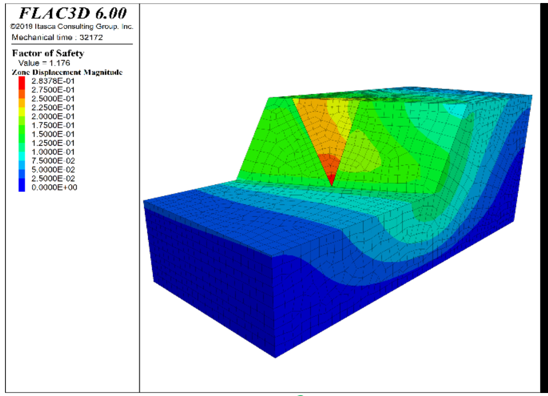
FoS



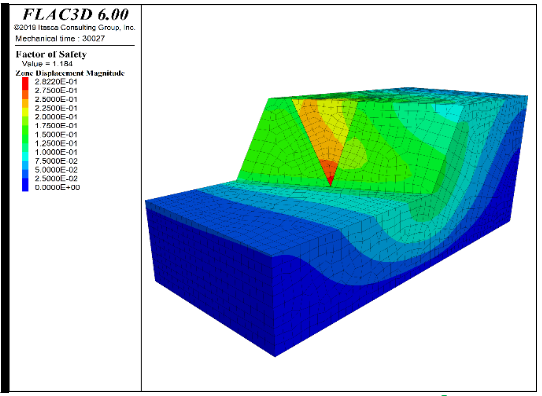
Uplift Forces, kN/m^3

Factor of Safety Versus Uplift Load

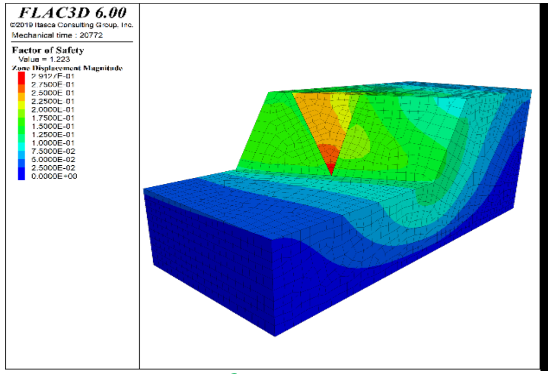
Verifications



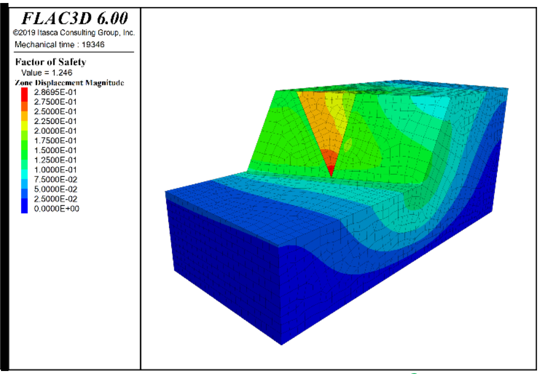
(a): U=4,0 (kN/m^3)



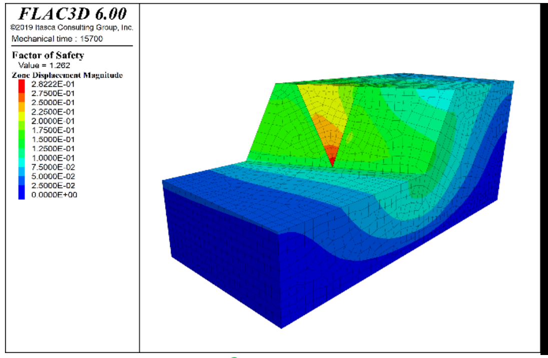
(b): U=3.7(kN/m^3)



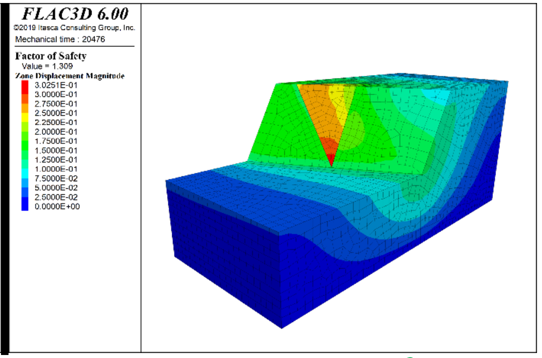
(c): U=3.4(kN/m^3)



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



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



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

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

Discussion

Table: Safety factor for 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
2.6	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

- From the presented data it is worthy of notice that each increase of the value of the uplift load, caused a decrease in the final value of the factor of safety.

Conclusion

- The study results entail that the presented analytical model can provide a robust analytical model for stability analysis of a slope subjected to wedge failure considering the presence of groundwater.
- The investigation results indicate that the presence of groundwater has impact on the computed Factor of Safety (FoS) of the slope subjected to wedge failure.

References

- Brehaut, R. J. (2009). Groundwater , Pore Pressure and Wall Slope Stability – a model for quantifying pore pressures in current and future mines . by. University of Canterbury, New Zealand.
- Bowa, V.M. (2020). 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
- Bui, X.N., Nguyen, H., Choi, Y., Nguyen-Thoi, T., Zhou, J., & 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), 1–17. https://doi.org/10.1038/s41598-020-66904-y
- Itasca Consulting Group, Inc. 2002. FLAC3D – Fast Lagrangian Analysis of Continua in 3 Dimensions, Ver. 2.1 User's Guide. Minneapolis: Itasca.
- Lancine, D, Chang S.G and Bowa, V.M. (2020) Influence of Rainfall Patterns on the Slope Stability of the Lumwana (the Malundwe) Open Pit. Geotechnical and Geological Engineering, an International Journal. 38(2):1337-1346.
- Wyllie, D.C. and Mah, C.W. (2004) Rock Slope Engineering, Civil and Mining. Fourth Edition, SPON Press, Madison, New York.

The End

THANK YOU FOR YOUR ATTENTION.