2024 ENGINEERING INSTITUTION OF ZAMBIA SYMPOSIUM

Development of 2D design charts for rock slopes susceptible to slide-head toppling failure.

PRESENTER : Abdul Samson

DATE : Friday 19th April 2024

Avani Victoria Falls Resort, Livingstone, Zambia

Contents

- Introduction
- The design chart Concept
- Development of 2D Design Charts
- Discussion
- Conclusion

Introduction

- Slide-head toppling failure is a secondary category of toppling which involves both sliding and toppling of rock blocks on a slope
- Analysis of this failure requires solving laborious complex equations
  - In determining toppling and sliding of rock blocks
- However, design charts prove to be handy in analyzing such failures
- A number of design charts have been developed for toppling failure and other failure mechanisms (wedge, circular, planar)
- Most design charts are developed based on the limit equilibrium equations
- Furthermore, previous design charts for toppling have been developed based on;

Introduction Cont'

- discontinuity friction angles
- the height to width ratio
- slope angles, as well as inter-block forces (Zanbak, 1983; Cruden, 1989; Yagoda-Biran and Hatzor, 2013)

- Further research observations have noted that in some physical circumstances the failure plane for toppling blocks may not be regular as previously assumed (Zuo et al., 2005; Cai, 2013; Bowa and Xia, 2018; Bowa and Gong, 2021)
- Due to among other geological conditions within the rockmass, the failure plane may counter-tilt and daylight anywhere else on the slope other than the originally assumed slope toe.

Introduction Cont’

- On another hand, the failure plane conditions such as roughness, smoothness as well as infill material.
- Which have a direct effect on the overall friction can result in the variation of the base friction and the inter-block friction
- This eventually leads to the notion of the possible variation of the base and inter-block friction resistances $(\phi_p \neq \phi_d)$
- In the case of toppling failure, specifically slide-head toppling

Design Charts Concept

- Determination of slide-head toppling is two-fold
- Thus toppling and sliding of blocks

With the two limit equilibrium equations as follows;

$$P_{n-1,t} = \frac{\frac{W_n}{2}(y_n sin\psi_c - \Delta x cos\psi_c) + P_n(M_n - \Delta x tan\phi_d)}{L_n} \quad \ldots.(1)$$

$$P_{n-1,s} - P_n = -\frac{W_n(cos\psi_c tan\phi_p - sin\psi_c)}{(1 - tan\phi_p tan\phi_d)} \quad \ldots.(2)$$

Design Charts Concept Cont’

- Where; $P_{n-1,t}$, $P_{n-1,s}$ $and\ P_n$, represent forces
- ψ_c denotes initial failure plane (before counter-tilting)
- ϕ_p denotes the base friction resistance
- ϕ_d denotes the inter-block friction resistance
- W_n denotes the weight of the rock block under consideration

Figure below illustrates the general slide-head toppling failure concept as well as the application of the two equations highlighted above.

Design Charts Concept Cont’

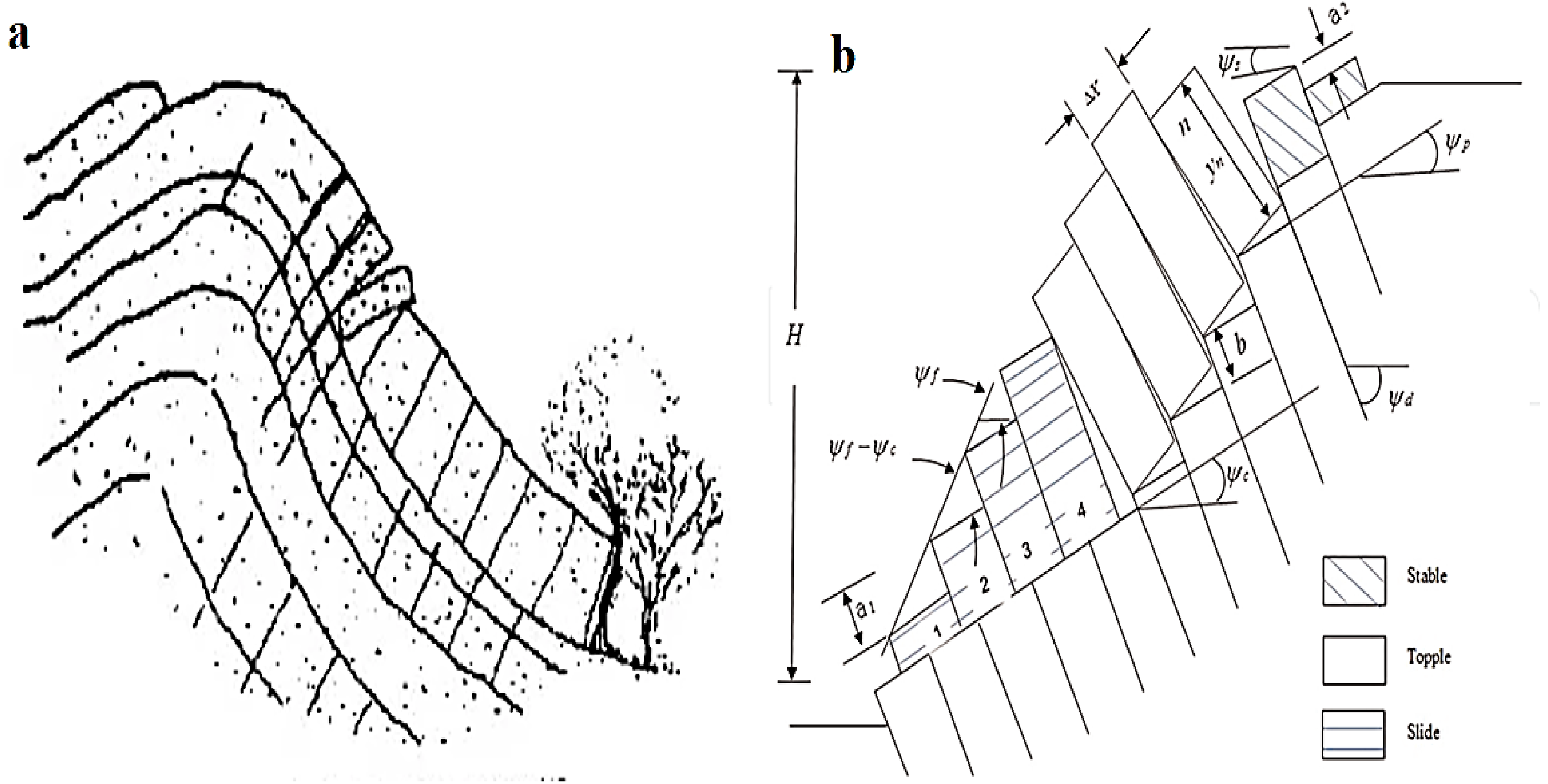


Fig 1: Conceptualisation of Slide-head toppling failure: (a) The general slide-head toppling failure concept as originally illustrated by Goodman and Bray (1976); (b) Schematic illustration of the toppling and sliding sections of a slope undergoing slide-head toppling (Bowa and Samson, 2022; Bowa and Xia, 2018).

Design Charts Concept Cont’

- The governing equation for the previously developed charts as described by Zanbak (1983) were based entirely on Equation 1.
- Additionally, as seen from Equation 1, only the inter-block friction resistance affects the equation.
- As such, It is therefore, not possible to develop charts based on the proposed governing principle ($\phi_p \neq \phi_d$) for Equation 1.

Therefore,

- Taking into consideration of Equation 2 and bearing in mind of the possibility for the initial failure plane to undergo counter-tilting within the rockmass, the following modifications to the equation can be made;

Design Charts Concept Cont'

$$P_n - P_{n-1,s} = \frac{W_n(cos\psi_c tan\phi_c - sin\psi_c)}{(1 - tan\phi_c tan\phi_d)}$$

$$P_{n-1,s} = P_n - W_n(\zeta) \ldots .(3)$$

Where;

$$\zeta = \frac{(cos\psi_c tan\phi_c - sin\psi_c)}{(1 - tan\phi_c tan\phi_d)} \ldots (4)$$

From Equation 4, it is therefore noted that zeta (ζ) varies with respect to three variables namely; the base frictional resistance (ϕ_c), the inter-block frictional resistance (ϕ_d) and the weak plane angle (ψ_c) within the rockmass

Development of 2D Design Charts

- These developed slide-head toppling charts can be applied in both situations where there is existence of the counter-tilting of the failure plane or not
- Equations 3 and 4 govern the development of these design charts
- In the case of counter-tilting of the weak plane, in Equation 4, as the weak plane counter-tilts from the initial failure plane (ψ_c), can be designated as ψ_p.
- Hence, rewriting Equation 4 with respect to counter-tilting of the weak plane yields Equation 5 as below;

$$\zeta = \frac{(cos\psi_p tan\phi_c - sin\psi_p)}{(1 - tan\phi_c tan\phi_d)} \ldots.(5)$$

Development of 2D Design Charts.. Cont’

- From Equation 5 it can be perceived that the limiting value for the counter-tilted angle for all positive values of ζ is the base friction resistance.
- Thus;

$$\zeta = \begin{cases} \lim\limits_{\psi_c \to \phi_c} 0 \\ \lim\limits_{\psi_p \to \phi_c} 0 \end{cases} \quad \dots (6)$$

- The charts have been developed using MATLAB software (The MathWorks Inc. 2016)
- The parameter zeta (ζ)is plotted against inter-block friction resistance (ϕ_d) for various values of counter-tilted weak plane angles (ψ_p) with reference to a constant base frictional resistance (ϕ_c) for each chart.

Development of 2D Design Charts.. Cont’

- The basal friction resistance therefore determines to what extent the counter-tilted angle can extend to from the original failure plane for all positive values of Zeta.
- For weak planes dipping at angles above the limiting basal friction (ϕ_c), it is observed that the design chart can be applied as a ‘mirror of itself’.
- From Equation 6, it is noted that the zeta (ζ) values become zero when the counter-tilted angle is or approaches the value of basal friction.
- Therefore, by calculation, it has been observed that each amount of addition to the failure plane angle equal to the basal friction is a negative replica of the same amount deducted from the basal friction angle.
- It is basically a negative mirror of its own/itself.

Development of 2D Design Charts.. Cont’

- For instance, the zeta (ζ) values of weak plane of 30^0 are an exact mirror of the weak plane of 40^0 in the negative form for the 35^0 basal friction chart.
- In summary, the following Equations 7 to 9 are true and govern the preceding observations;

$$\zeta, (\phi_c - x) = -\zeta, (\phi_c + x) \ldots (7)$$

For any integer values of x,

Where $(\phi_c - x)$ and $(\phi_c + x)$ are designated values of ψ_p

Furthermore,

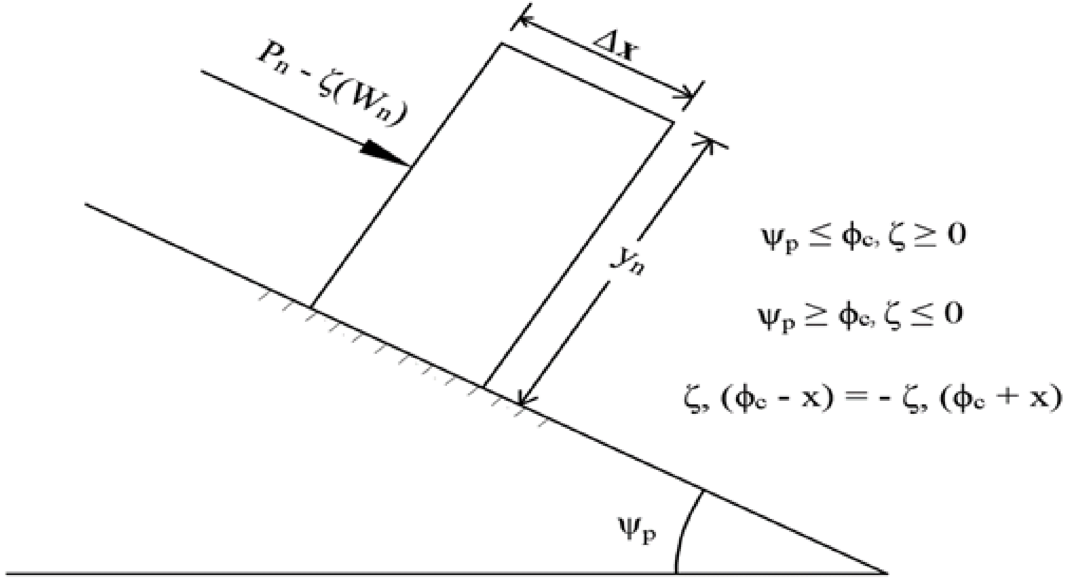
$$\zeta \geq 0, for\ \psi_p \leq \phi_c \ldots (8)$$

Development of 2D Design Charts.. Cont’

And

$$\zeta \leq 0, for\ \psi_p \geq \phi_c \ldots (9)$$

Figure 2 depicts the principle on which the developed charts have been based on with reference to the sliding rigid rock blocks and the equations that govern it described above;



Developed Charts

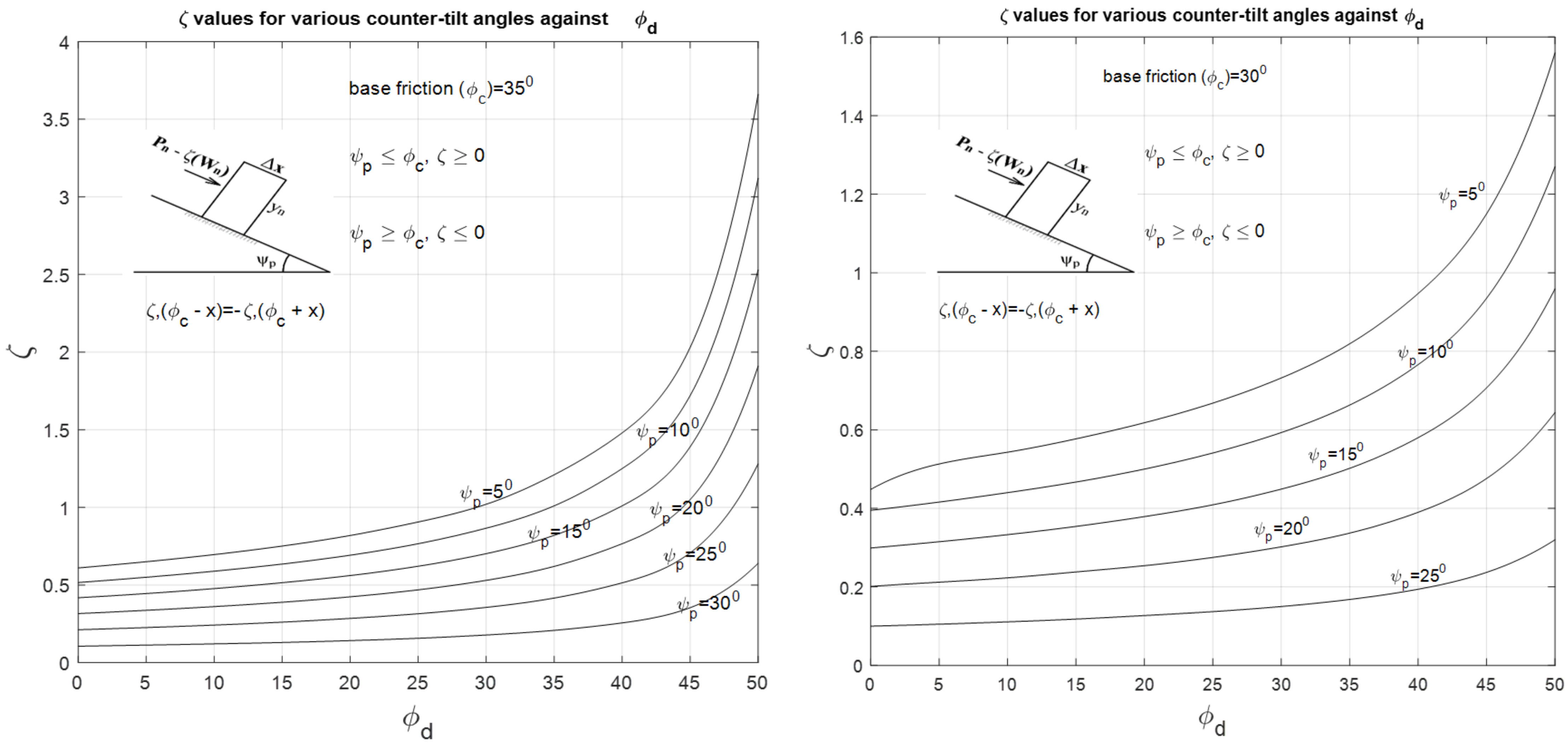
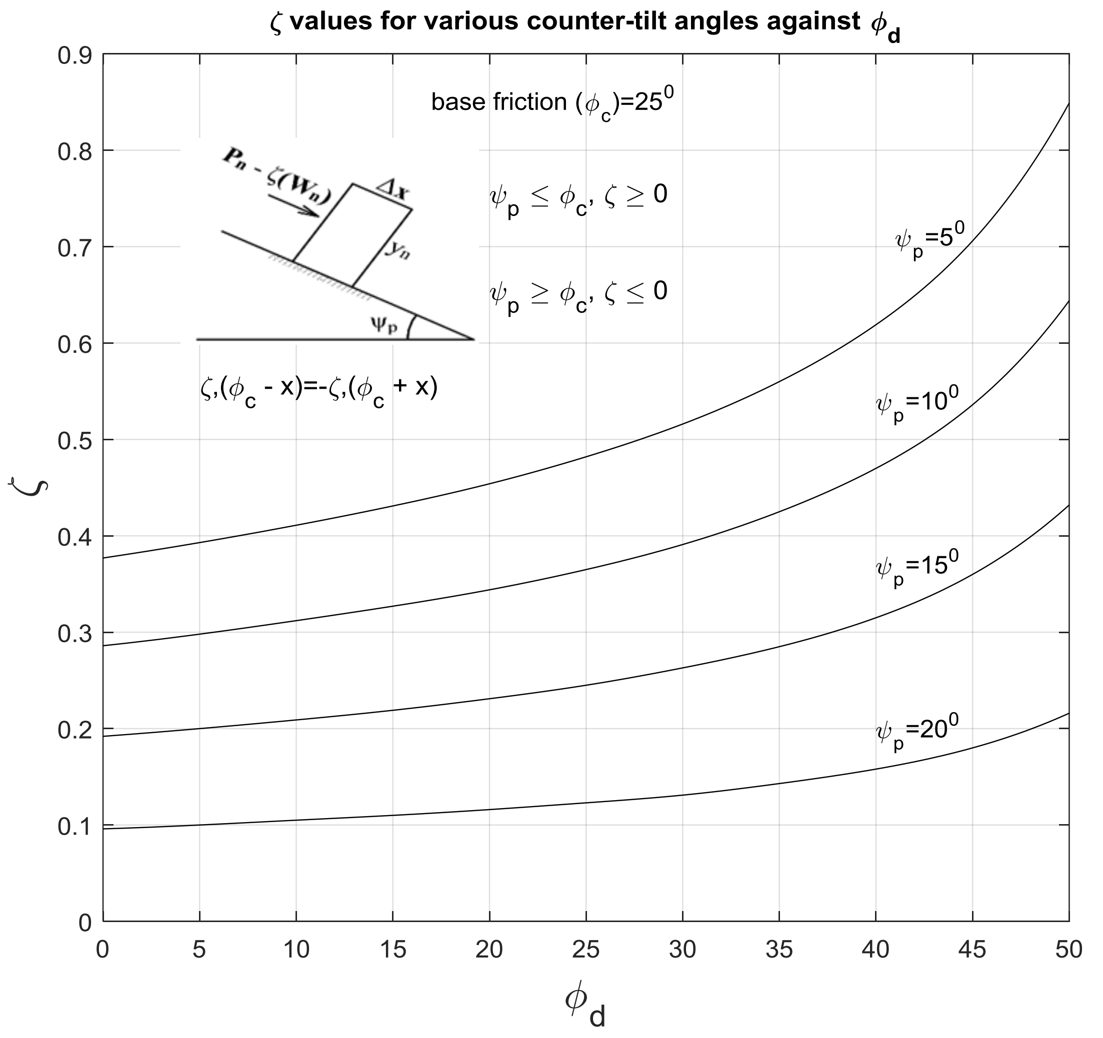


Fig. 3: Developed 2-dimensional design chart for various weak plane and counter-tilt angles (ψ_p) against inter-block friction resistance (ϕ_d); (i) basal friction angle of 35^0, (ii) basal friction angle of 30^0, (iii) basal friction angle of 25^0

Developed Charts



Discussion and Conclusion

- The development of the charts has been done on the premise that the base friction is different from the inter-block friction resistance ($\phi_p \neq \phi_d$)
- The charts aim to provide a preliminary check on the possibility for sliding of rock blocks under slide-head toppling in counter-tilted rock slopes. But can also be applied in situations of normal failure planes.
- The charts can be utilised in two ways:

I. In situations that support Equation 6 as provided in the preceding sections

II. Where the base friction is less than the failure plane angle for slide-head toppling (equation 7)

- To obtain Zeta (ζ), the two friction resistances (base and inter-block friction) need to be provided and properly defined.

Discussion and Conclusion

- For curiosity's sake, the principle on which these charts have been developed ($\phi_p \neq \phi_d$) using Equation (2) may not be possible to apply for the development of similar charts based on Equation (1).
- The variables and /or parameters that govern a rock block to undergo toppling on a slope do not depend on/include the base friction.

Way forward

- Further research is planned to simulate conditions of counter-tilting of the failure plane within the rockmass as highlighted in the preceding paragraphs.
- This will be achieved through the use of both numerical and experimental modelling.

The End

THANK YOU FOR YOUR ATTENTION.

the Engineering Institution of Zambia