3D Effects of permeability and strength anisotropy on the stability of weakly cemented rock slopes subjected to rainfall infiltration

Po-Tsun Yeh, Kevin Zeh-Zon Lee, Kuang-Tsung Chang, 2020.

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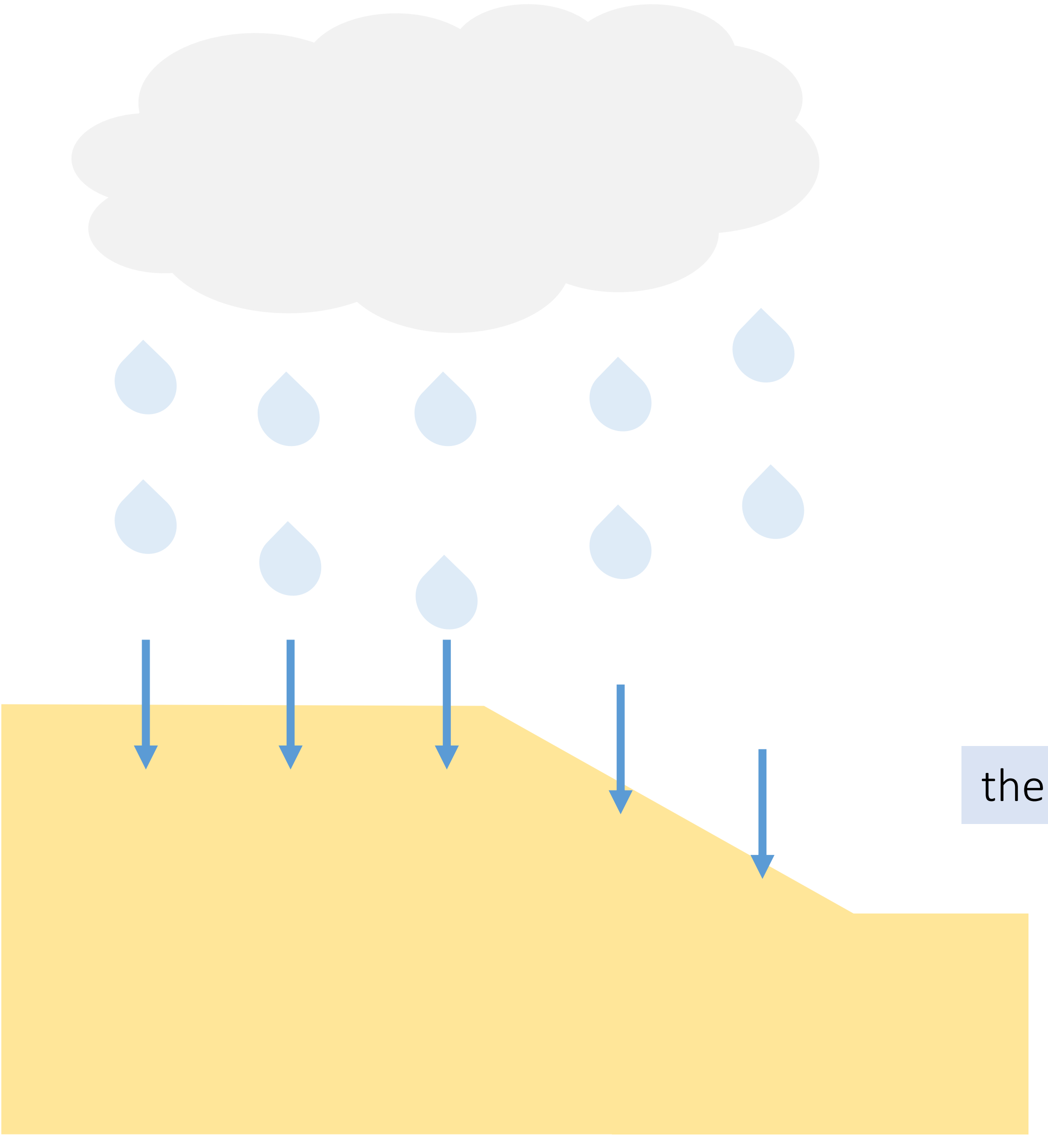
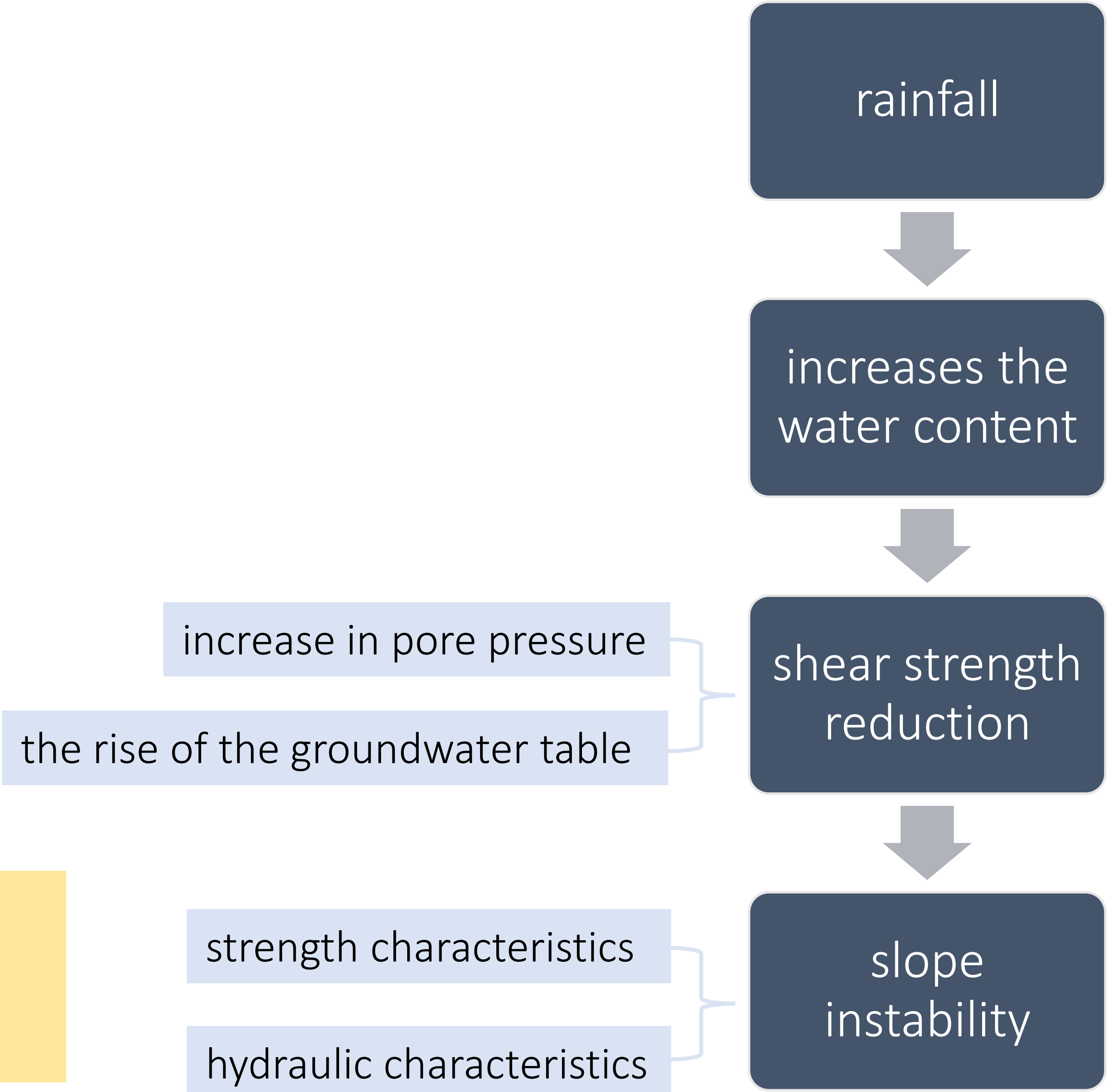
Advisor: Jia-Jyun Dong
Date: 2022.05.27

Introduction

Introduction





rainfall

increases the water content

shear strength reduction

slope instability

increase in pore pressure

the rise of the groundwater table

strength characteristics

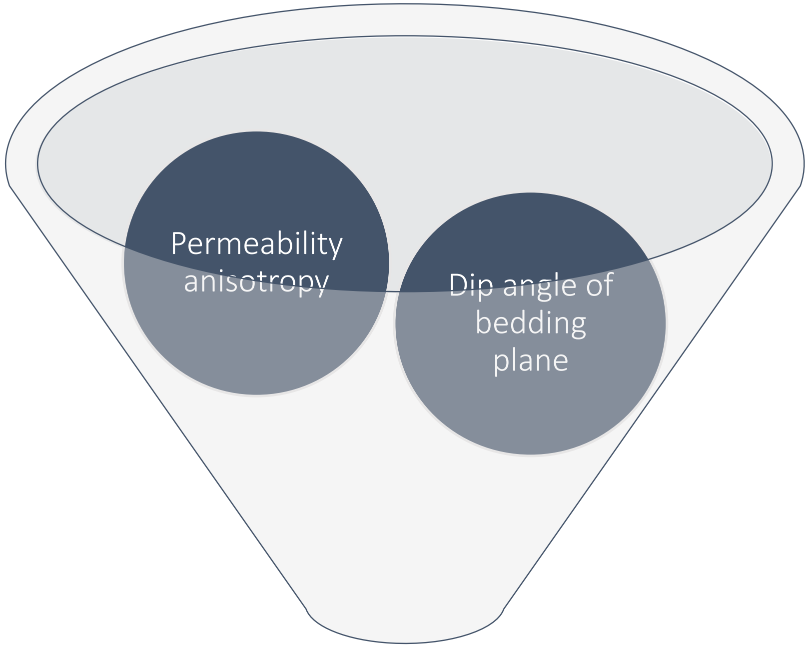
hydraulic characteristics

(Collins et al., 2004)

(Cai et al., 2004)

Previous studies

steady state

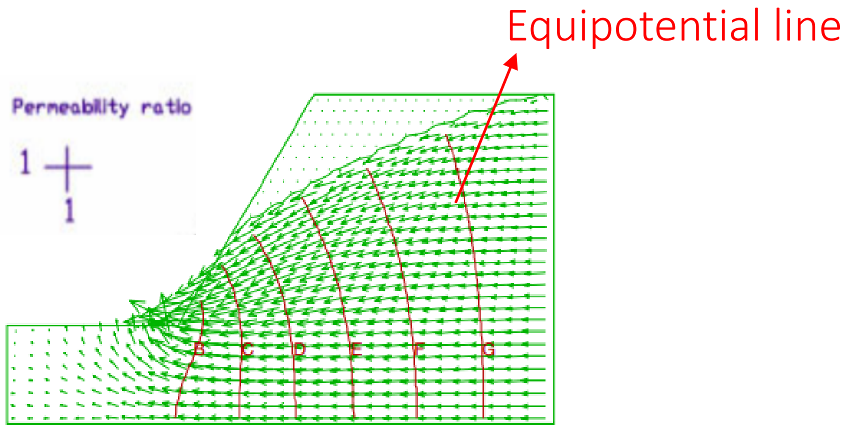


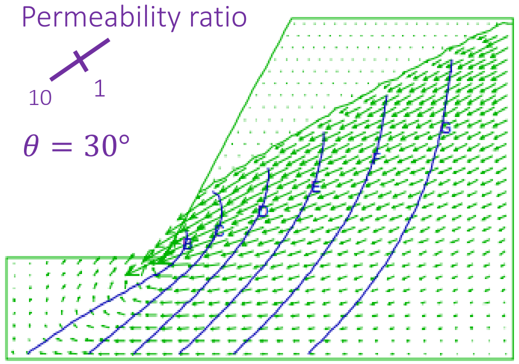
Permeability anisotropy

Dip angle of bedding plane

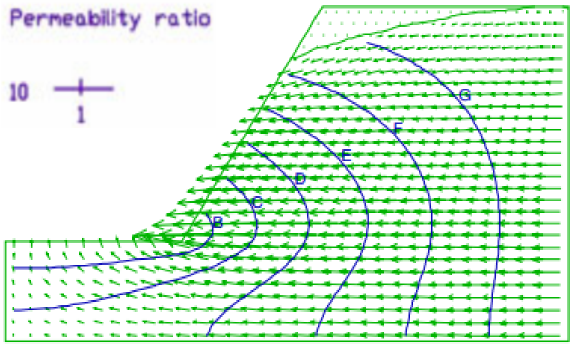
Distribution of pore water pressure

Slope stability





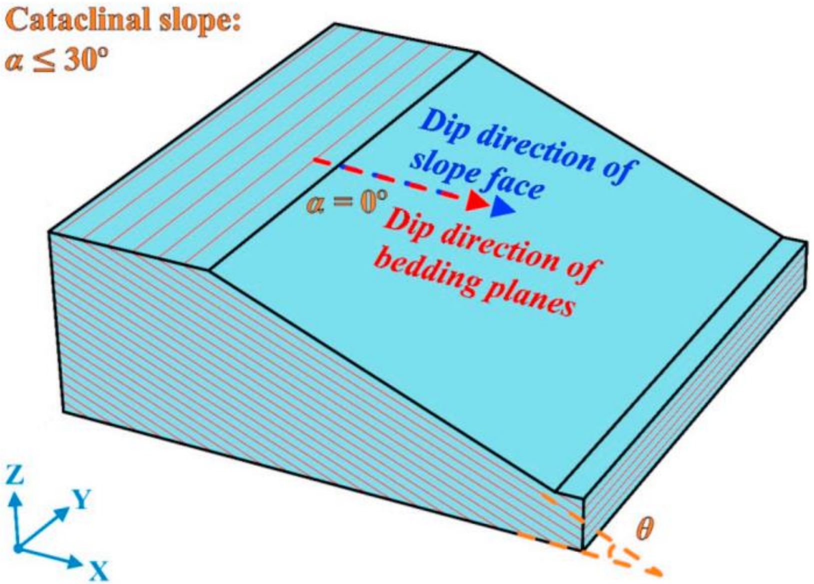
(Dong et al., 2012)

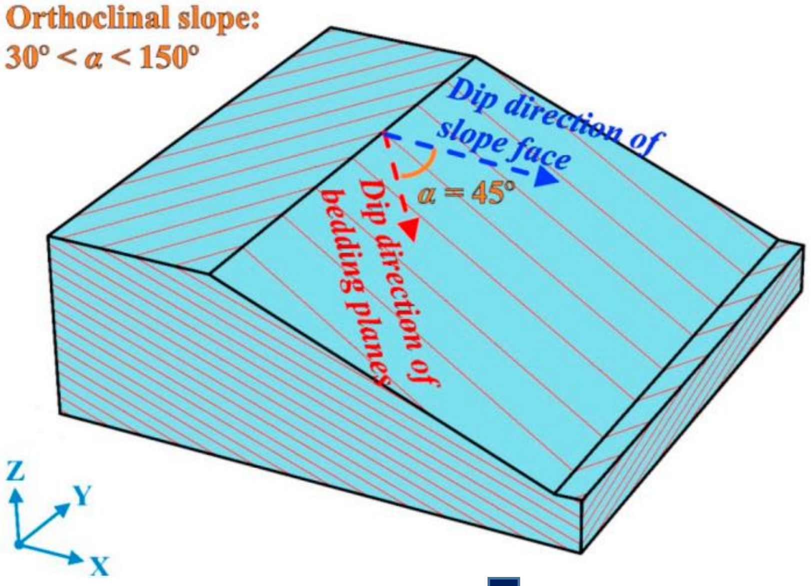


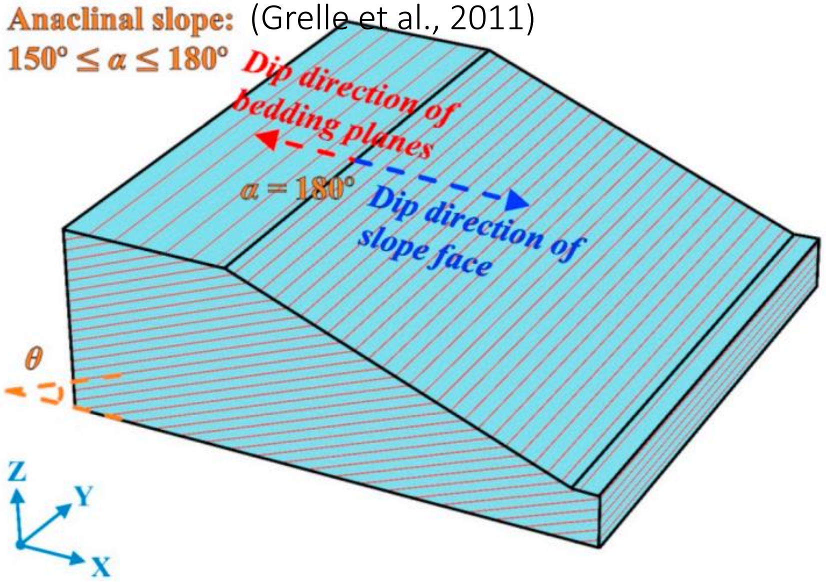
(Sharp et al., 1972)

Purpose

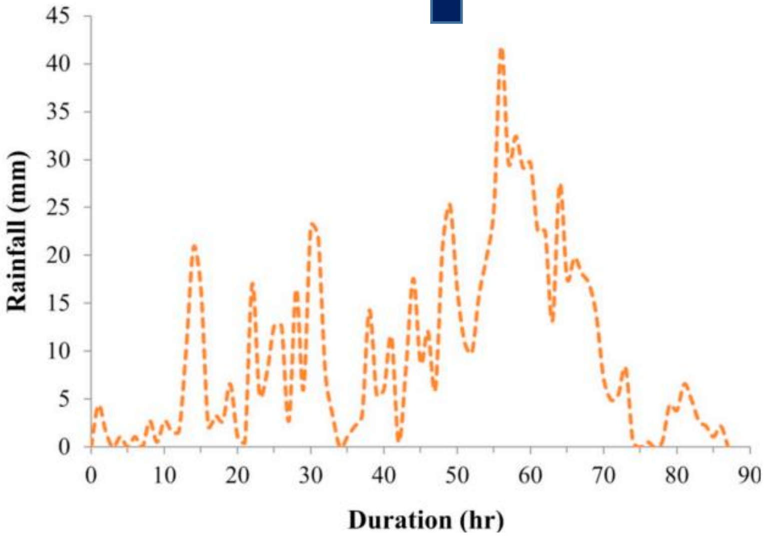
(The slope angle = 21.5°.)







(Grelle et al., 2011)



Numerical simulation

Numerical simulation

Model setup

Geology condition	Material properties	Boundary condition	Initial condition

(The slope angle = 21.5°.)

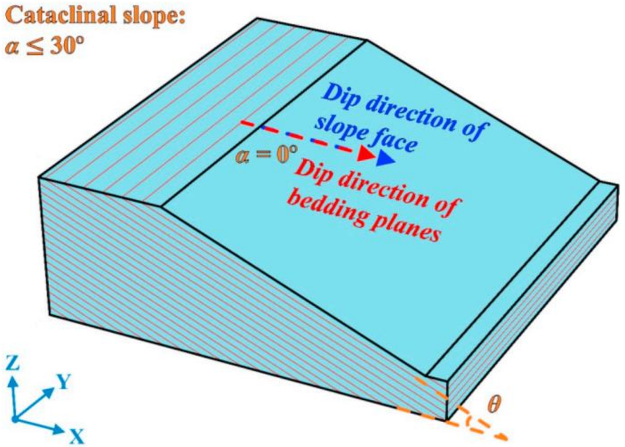
Examine the model response

Check results unsatisfactory

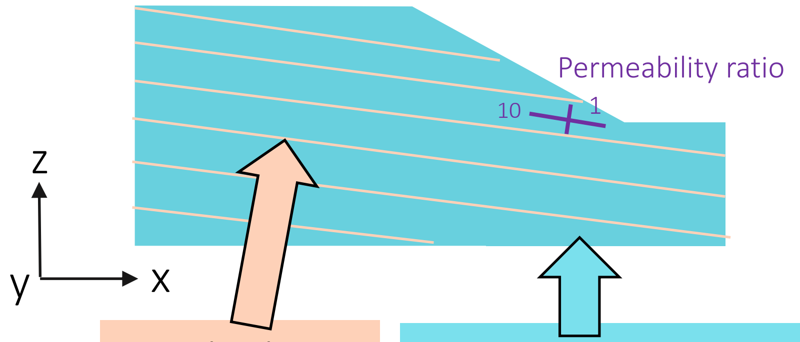
Perform alteration

Change parameter (α & θ)

Result and discussion



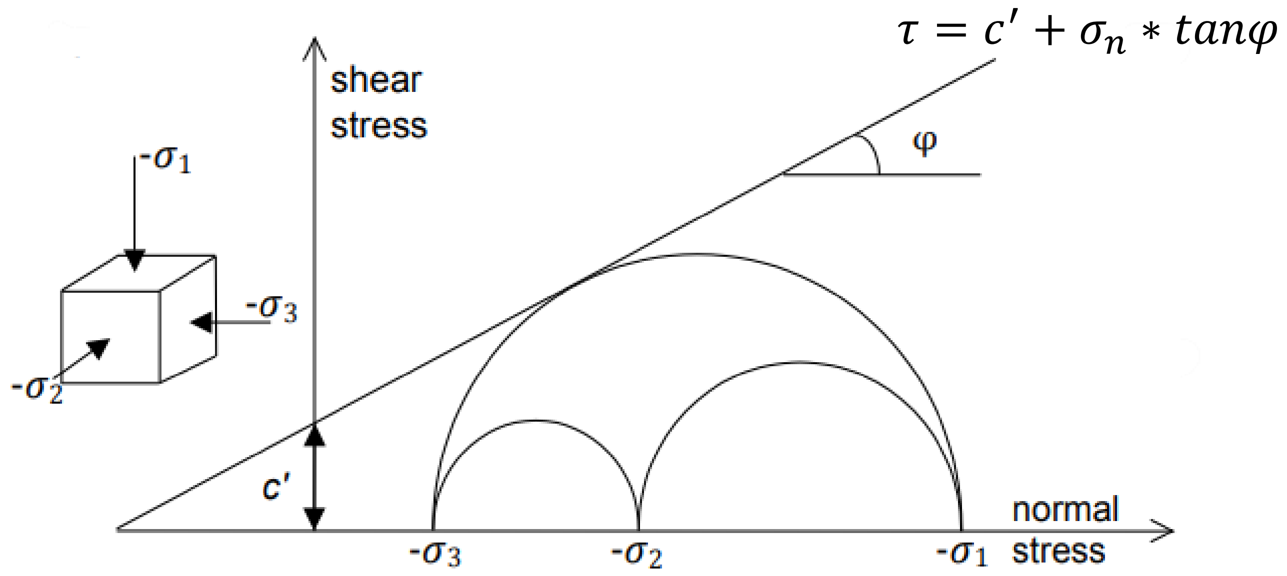
Material properties



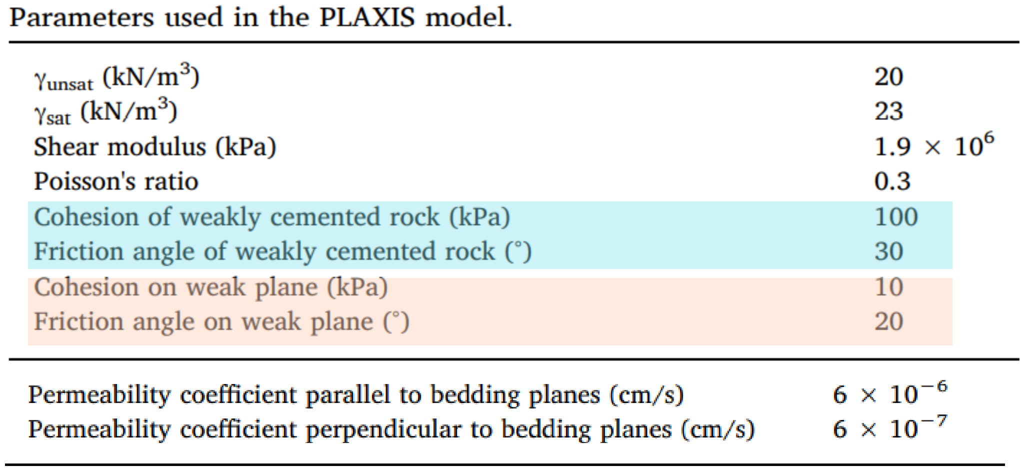
Weak plane

The thin bedded considered as a transversely isotropic medium. (x-direction = y-direction)

- Iso-JRMC model (PLAXIS BV., 2014): It combines the jointed rock model and the Mohr-Coulomb model.



$$\tau = c' + \sigma_n * tan\varphi$$

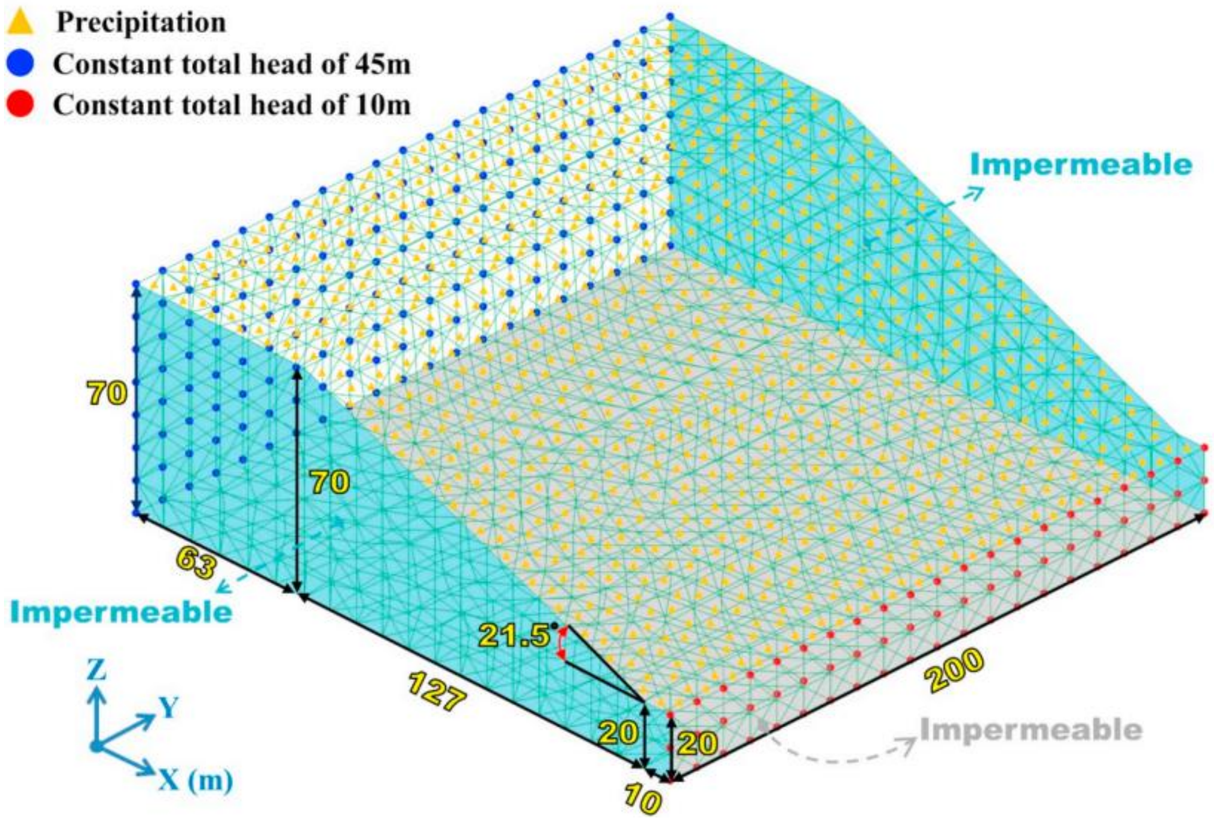


Parameters used in the PLAXIS model.

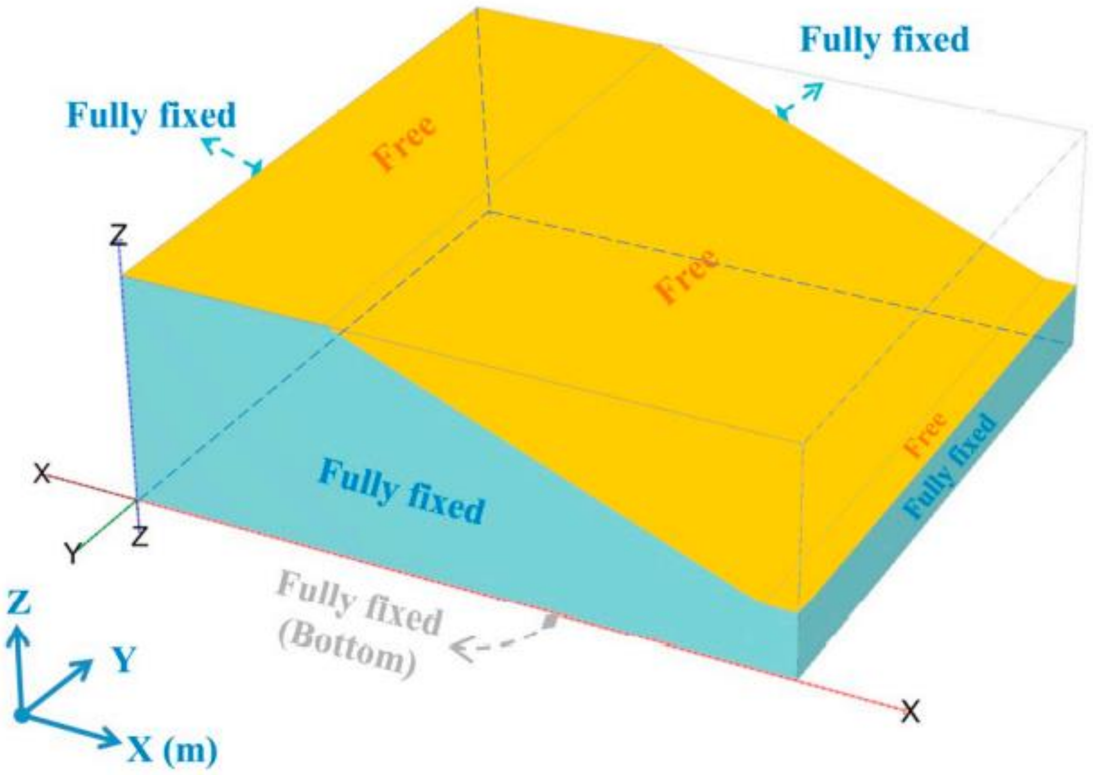
γ_{unsat} (kN/m^3)	20
γ_{sat} (kN/m^3)	23
Shear modulus (kPa)	1.9×10^6
Poisson's ratio	0.3
Cohesion of weakly cemented rock (kPa)	100
Friction angle of weakly cemented rock (°)	30
Cohesion on weak plane (kPa)	10
Friction angle on weak plane (°)	20
Permeability coefficient parallel to bedding planes (cm/s)	6×10^{-6}
Permeability coefficient perpendicular to bedding planes (cm/s)	6×10^{-7}

Boundary condition

Hydraulic Boundary

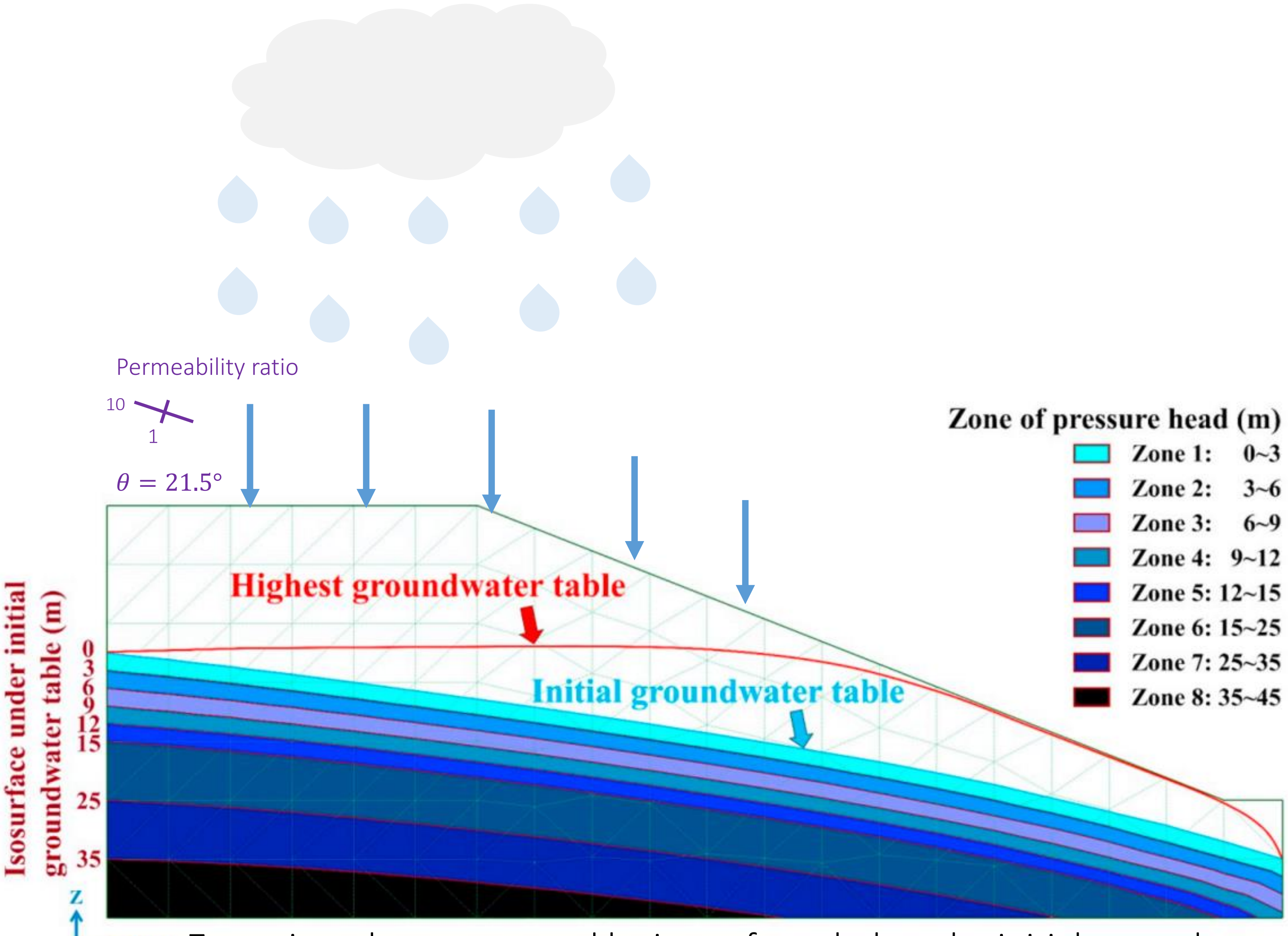


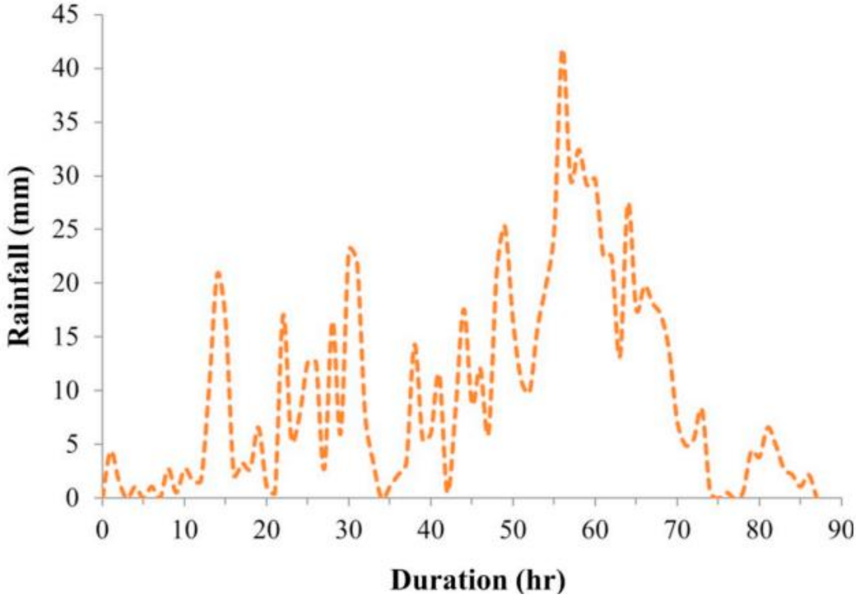
Mechanical Boundary



Initial condition ($\alpha = 0\ ;\ \theta = 21.5°$)

$(\theta = dip\ angle\ of\ bedding\ plane)(\alpha = dip\ direction\ of\ bedding\ plane)$



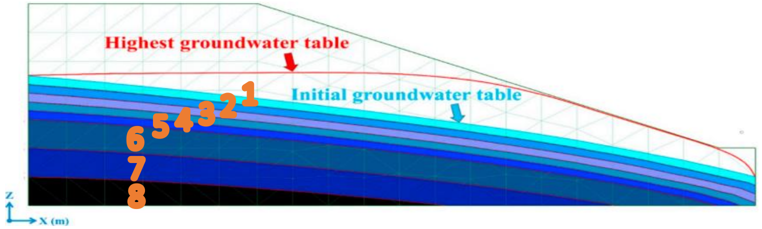


Zones in a slope separated by isosurfaces below the initial groundwater table.

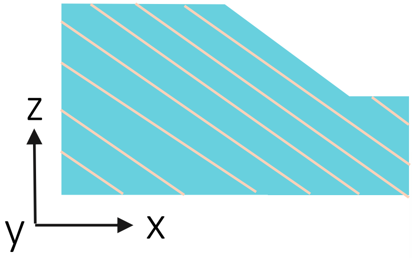
Results

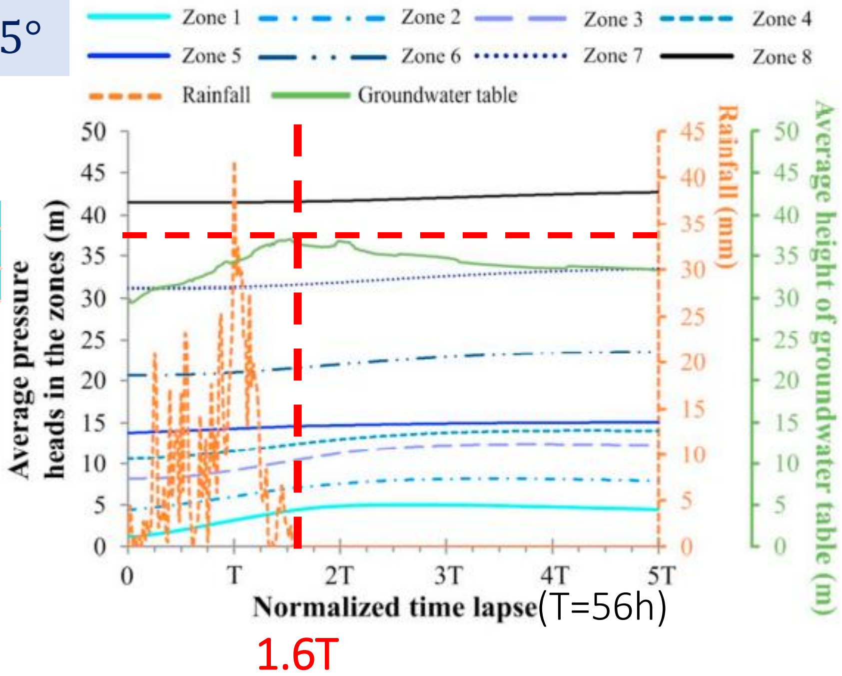
Compare with different θ

$(\theta = dip\ angle\ of\ bedding\ plane)(\alpha = dip\ direction\ of\ bedding\ plane)$

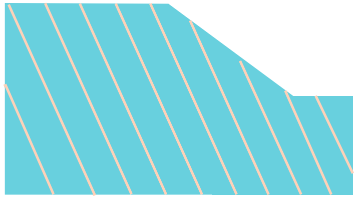


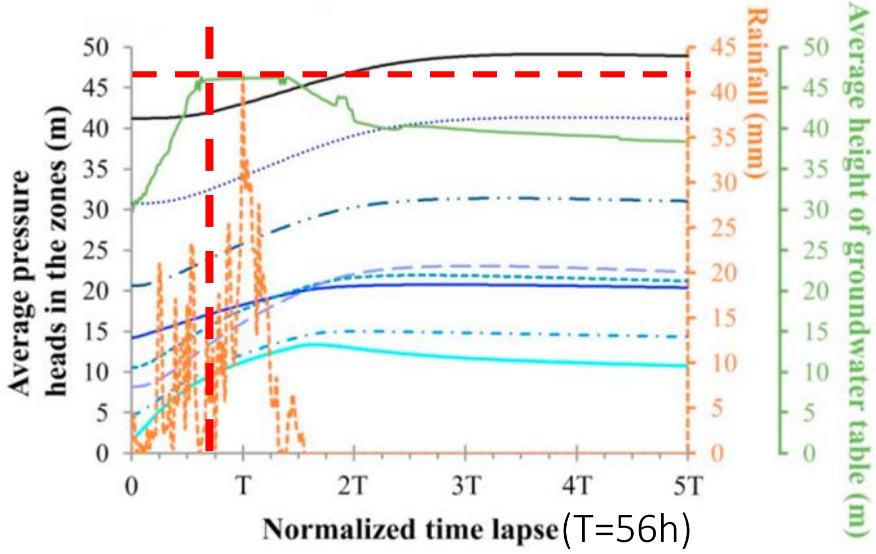
$\alpha = 0\ ;\ \theta = 21.5°$





$\alpha = 0\ ;\ \theta = 60°$

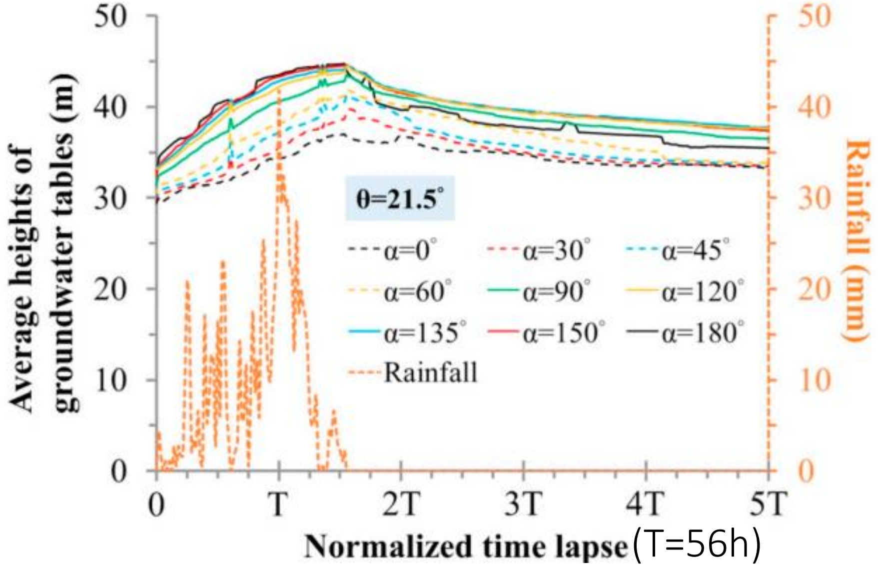


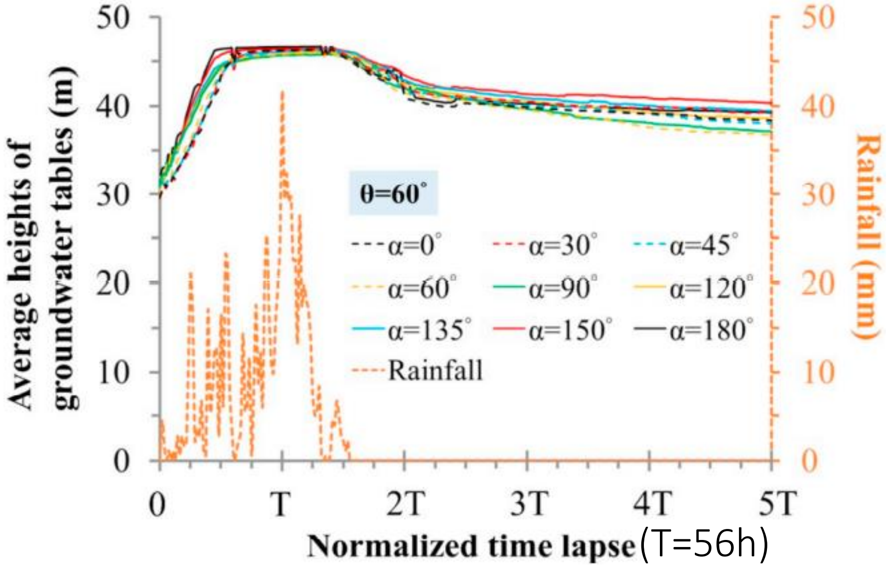


- Under the same rainfall condition, the result of $\theta = 60°$ showed greater rise of the average groundwater table and took shorter time to reach the highest groundwater table than the slope with $\theta = 21.5°$.
- The result of $\theta = 60°$ showed larger increases in the pressure head at different depths.

Compare with different α & θ

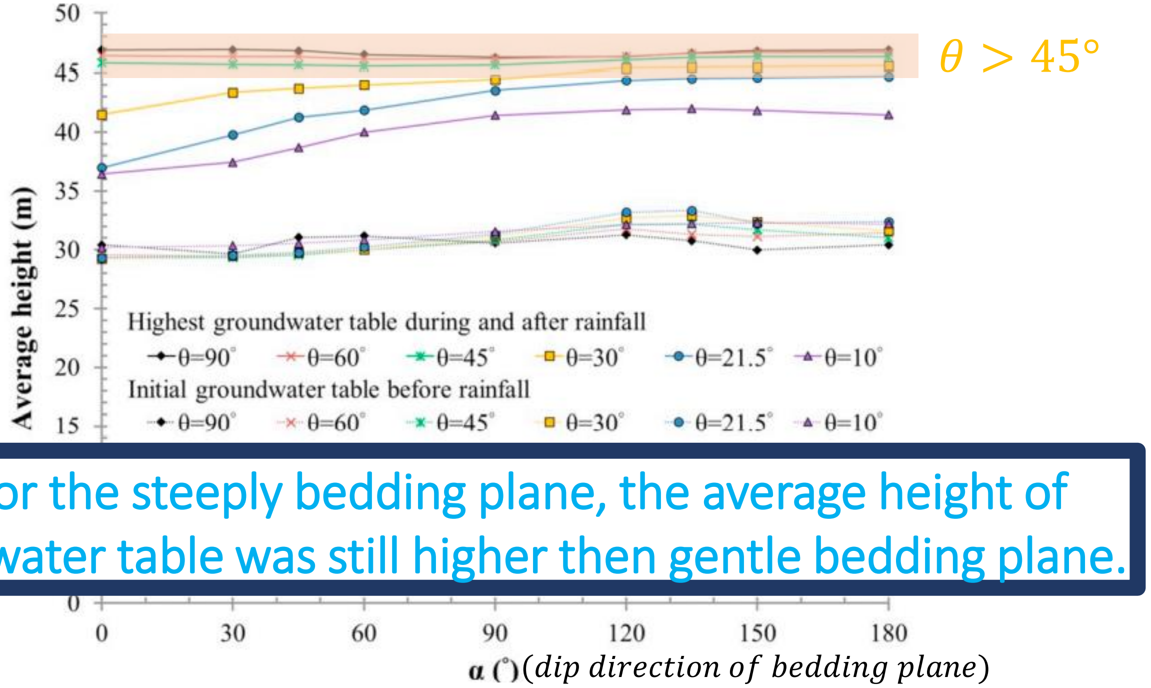
$(\theta = dip\ angle\ of\ bedding\ plane)(\alpha = dip\ direction\ of\ bedding\ plane)$





- For $\theta = 21.5^\circ$, the greater α, the higher value of average groundwater table. But for $\theta = 60^\circ$, it didn't indicate such a trend.

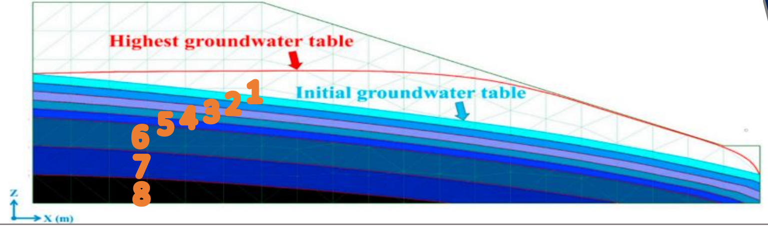
For those beddings planes having steep dip angle, the direction of bedding plane have no significance influence on the average height of groundwater table.

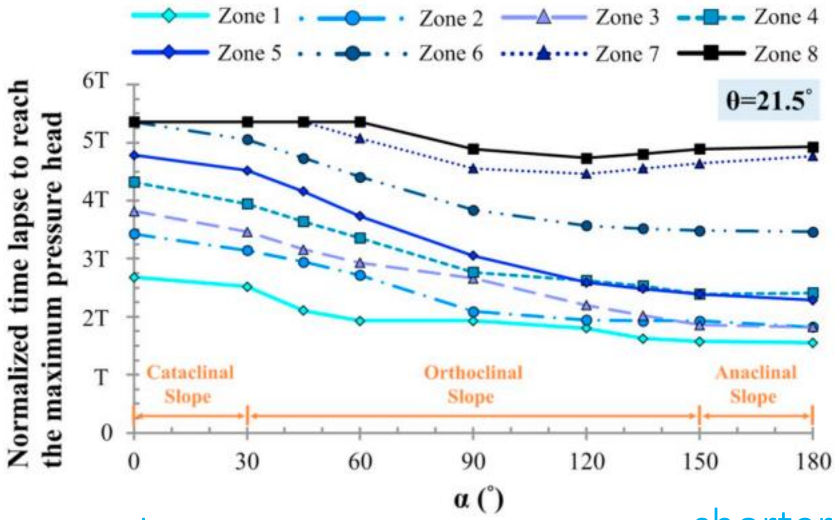


But for the steeply bedding plane, the average height of groundwater table was still higher then gentle bedding plane.

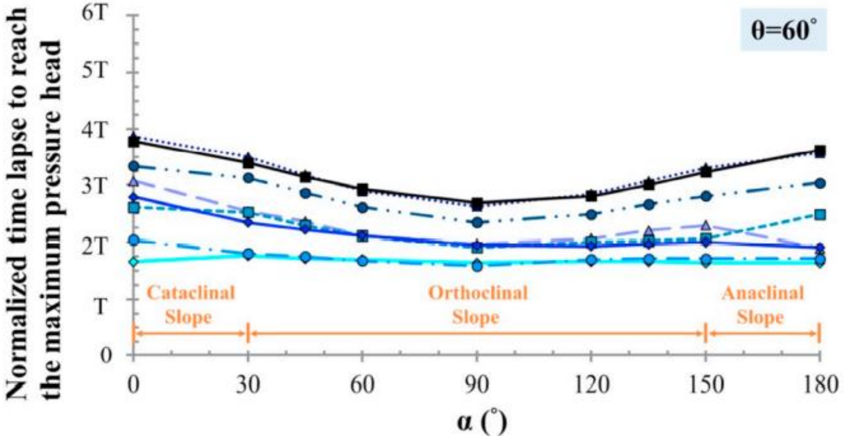
Compare with different α & θ

$(\theta = dip\ angle\ of\ bedding\ plane)(\alpha = dip\ direction\ of\ bedding\ plane)$





longer shorter



longer shorter longer

- For $\theta = 21.5°$, it showed that deeper zones took a longer time to reach the maximum pressure head. For $\theta = 60°$, it has same trend.

This was explained by the pore pressure diffusion process.

- For $\theta = 21.5°$, anaclinal slopes showed shorter time to reach the maximum pressure head at deeper zone.
- For $\theta = 60°$, orthoclinal slopes showed shorter time to reach the maximum pressure head at deeper zone.

The steeply bedding plane took shorter time to reach the maximum pressure head then gentle bedding plane.

Summary for different α & θ

$(\theta = dip\ angle\ of\ bedding\ plane)(\alpha = dip\ direction\ of\ bedding\ plane)$

Fix $\alpha = 0$

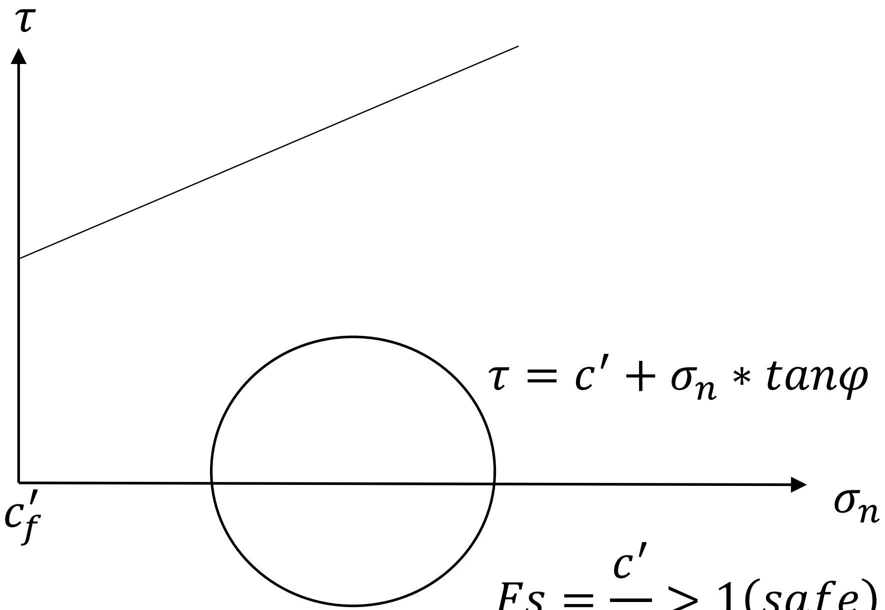
The dip angle of bedding planes	21.5°	60°
Time to reach highest groundwater table	Longer	Shorter
Rise of groundwater table	Lower	Higher
Increase of pressure head at a certain position	Smaller	Larger

Fix $\theta = 60°$

The dip direction of bedding planes	Cataclinal slopes $(\alpha < 30°)$	Orthoclinal slopes $(30° < \alpha < 150°)$	Anaclinal slopes $(\alpha > 150°)$
The average of groundwater table	Roughly same		
Time to reach maximum pressure head at a certain position (e.g. Zone 4 at depth of 9-12m)	Longer	Shorter	Longer

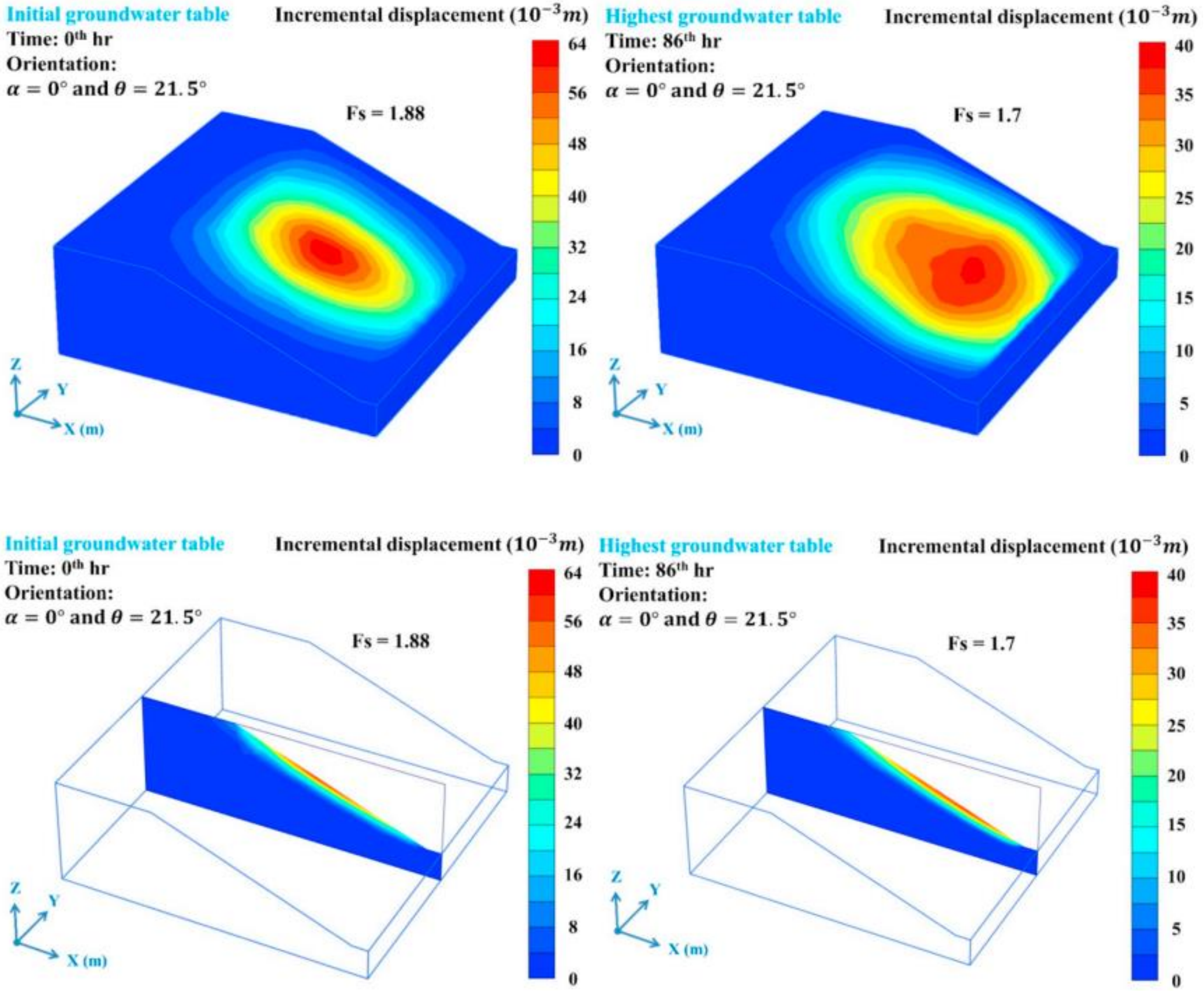
Slope stability

- The factor of safety is based on the shear strength reduction technique.
- The essence of shear strength reduction technique is the reduction of the soil strength parameters until the soil fails.



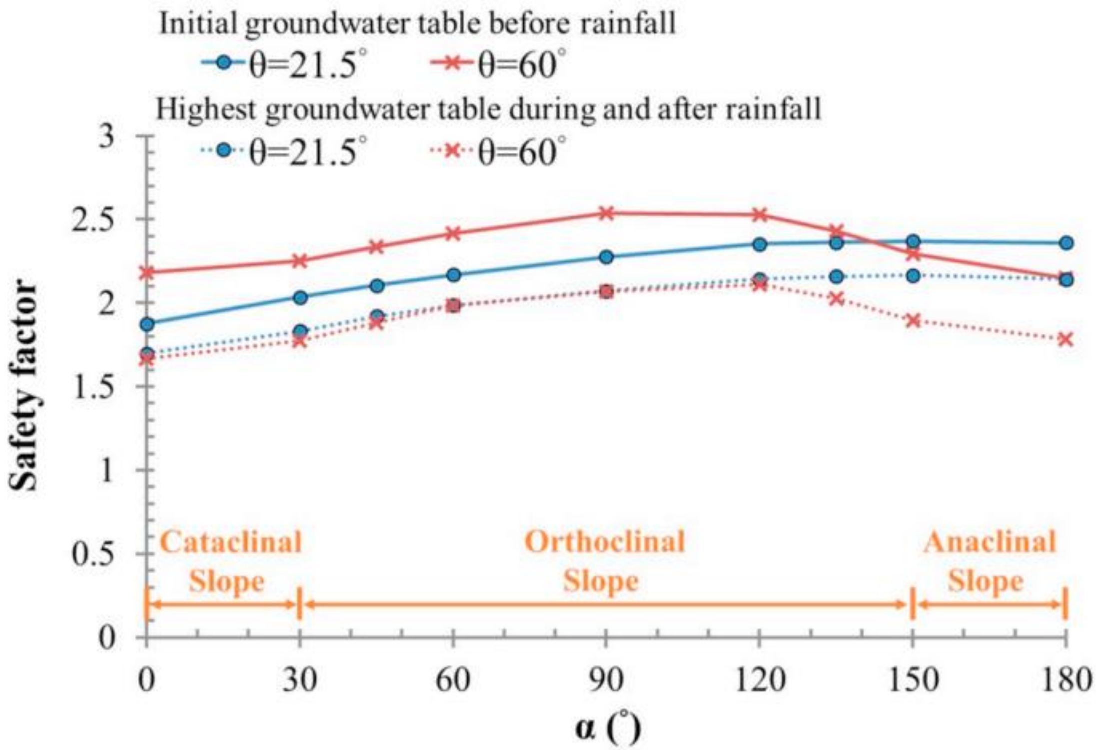
$$\tau = c' + \sigma_n * tan\varphi$$

$$Fs = \frac{c'}{c_f'} > 1(safe)$$
$$\leq 1(unsafe)$$



Results for slope stability

$(\theta = \mathit{dip\ angle\ of\ bedding\ plane})(\alpha = \mathit{dip\ direction\ of\ bedding\ plane})$



Same trend

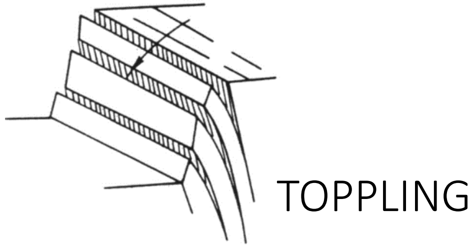
- ➢ The rise of the groundwater table or pore pressure caused a reduction in the factor of safety.

$\theta = 21.5°$(gentle bedding plane)

- ➢ The greater angle of α, the greater factor of safety were shown.

$\theta = 60°$(steeply bedding plane)

- ➢ Because it has higher groundwater table and more increase of pore pressure, causing the smaller safety factor then the gentle bedding plane.
- ➢ The smaller factors of safety appeared at $\alpha = 0° \ \& \ 180°$, the failure mode may be related to toppling. (Nichol et al., 2002)

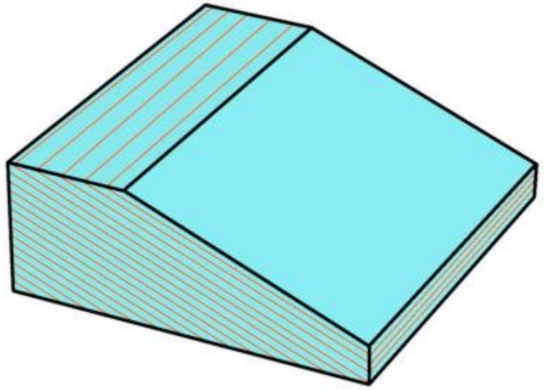


Discussions

Discussions

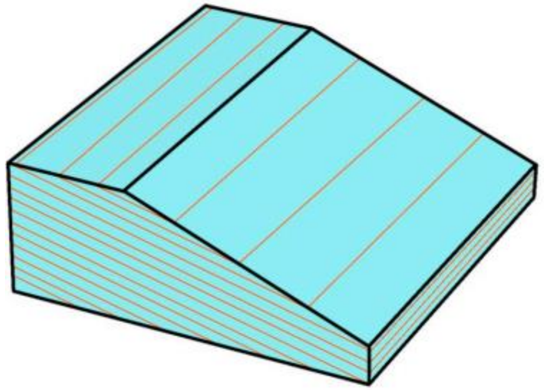
$(\theta = dip\ angle\ of\ bedding\ plane)(\alpha = dip\ direction\ of\ bedding\ plane)$

The unfavorable bedding plane-slope conditions for slope stability:



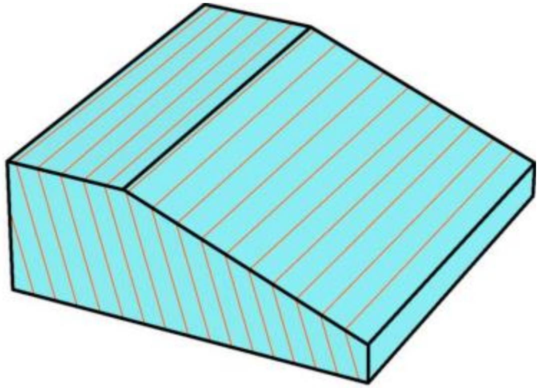
(a)

$\theta =$ slope angle ; $\alpha = 0^\circ$
(cataclinal dip slope)



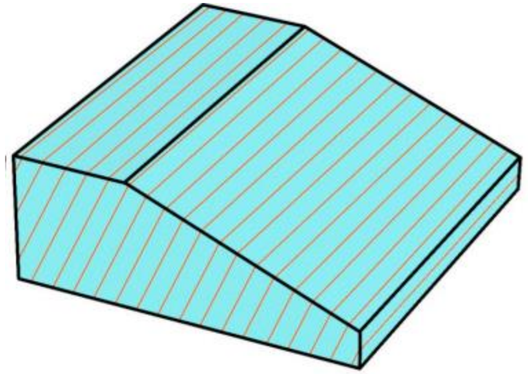
(b)

$\theta <$ slope angle ; $\alpha = 0^\circ$
(cataclinal under-dip slope)
(daylight condition)



(c)

$\theta >$slope angle ; $\alpha = 0^\circ$
(cataclinal over-dip slope)

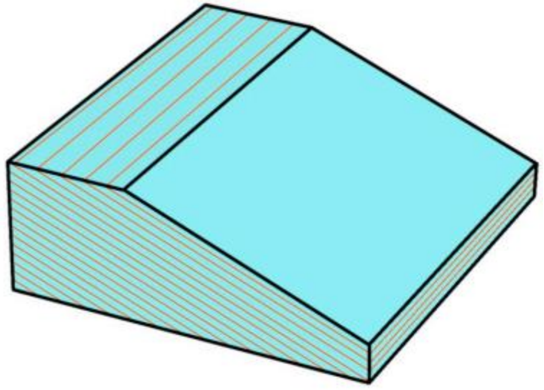


(d)

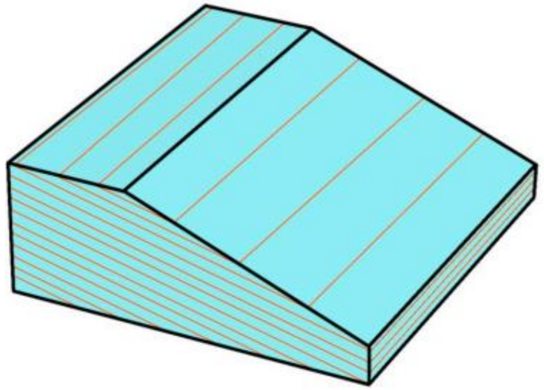
$\theta >$ slope angle; $\alpha = 180^\circ$
(anaclinal slope)

Discussions

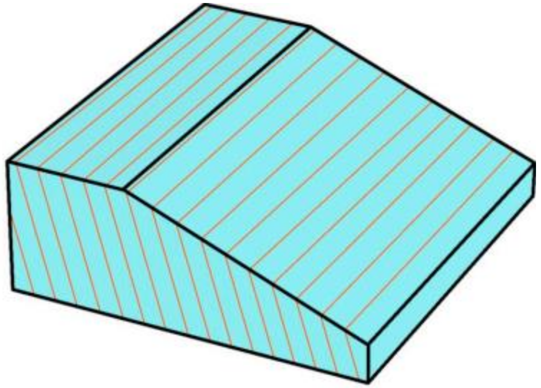
The unfavorable bedding plane-slope conditions for slope stability:



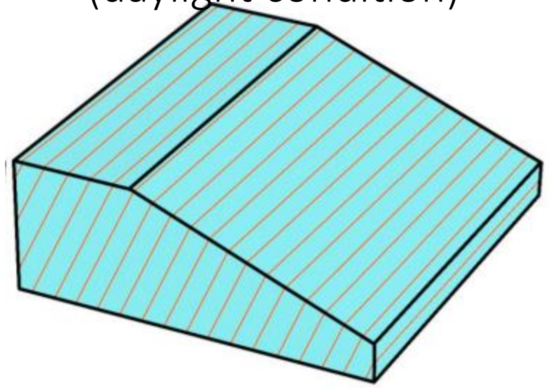
$\theta =$ slope angle ; $\alpha = 0^\circ$
(cataclinal dip slope)



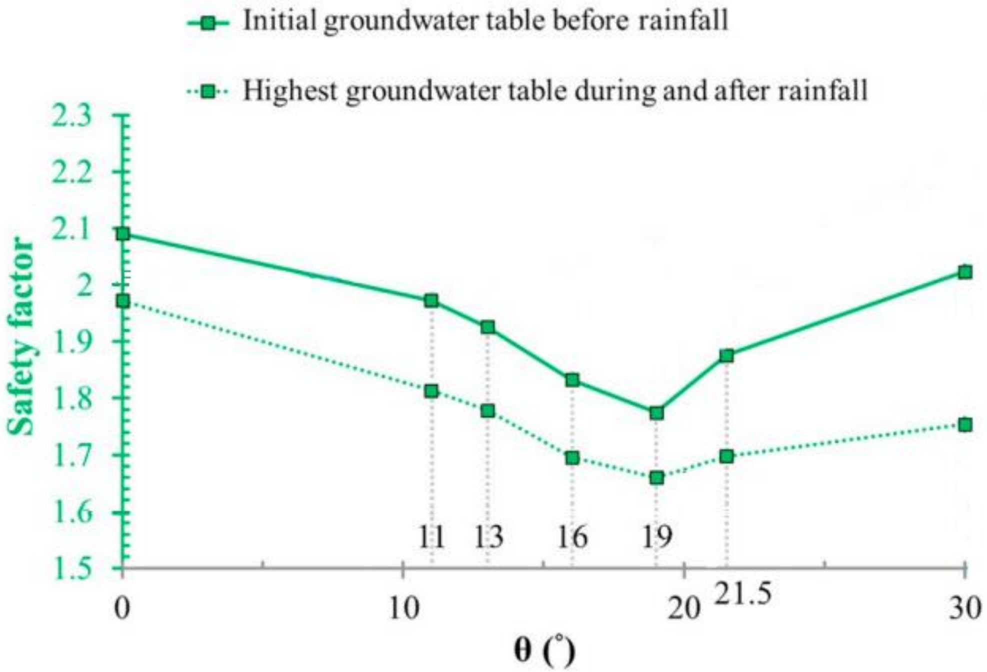
$\theta <$ slope angle ; $\alpha = 0^\circ$
(cataclinal under-dip slope)
(daylight condition)



$\theta >$slope angle ; $\alpha = 0^\circ$
(cataclinal over-dip slope)



$\theta >$ slope angle; $\alpha = 180^\circ$
(anaclinal slope)

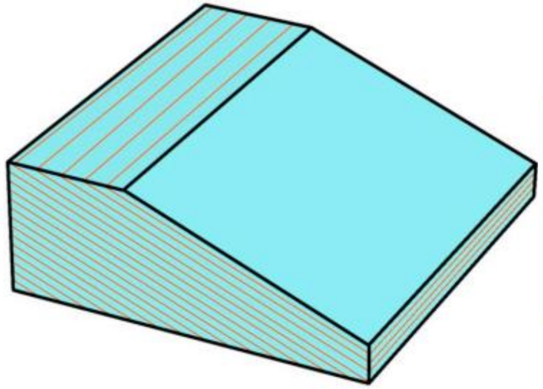


- ➢ Where the joint plane is exposed in the slope face, the plane is regarded to "daylight", a condition may lead to rock mass sliding.
- ➢ The daylight condition might exist in natural slopes due to the incision of rivers; however, weathering will eventually weaken the strength of weak planes, and the slope fails along the daylight weak planes.

Discussions

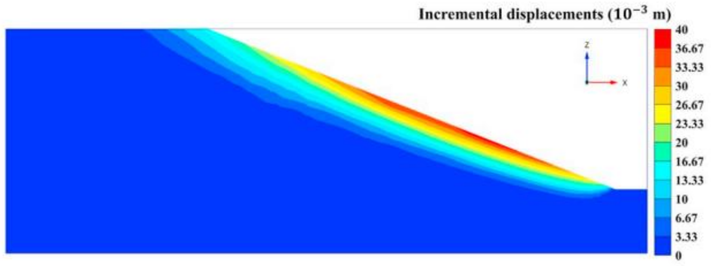
$(\theta = dip\ angle\ of\ bedding\ plane)(\alpha = dip\ direction\ of\ bedding\ plane)$

The unfavorable bedding plane-slope conditions for slope stability:

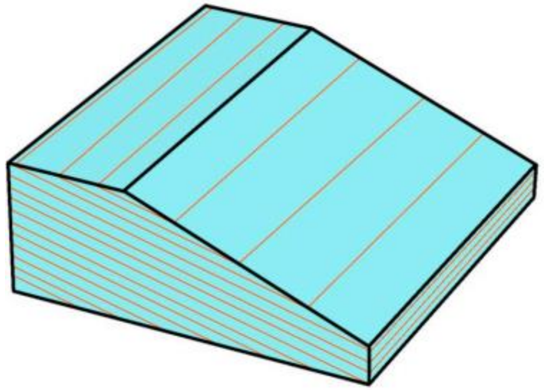


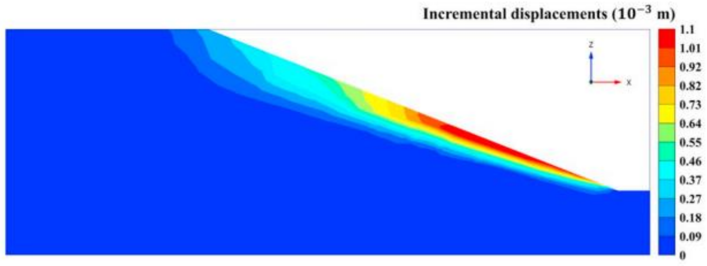
(a)

θ = slope angle
(cataclinal slope)



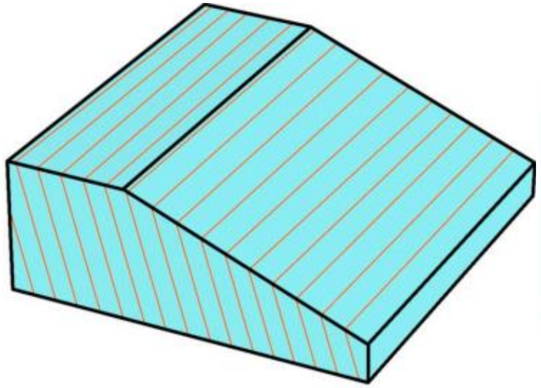
(a)





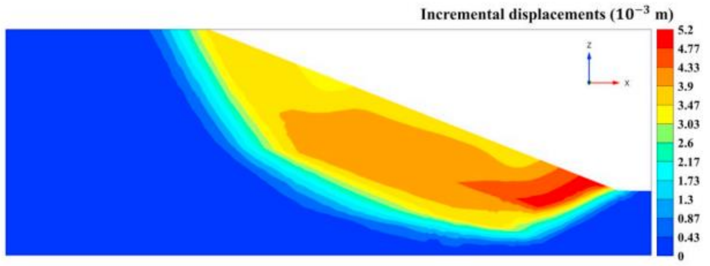
(b)

Therefore, the two conditions in (a) and (b) may be considered more unfavorable than the two conditions in (c) and (d).

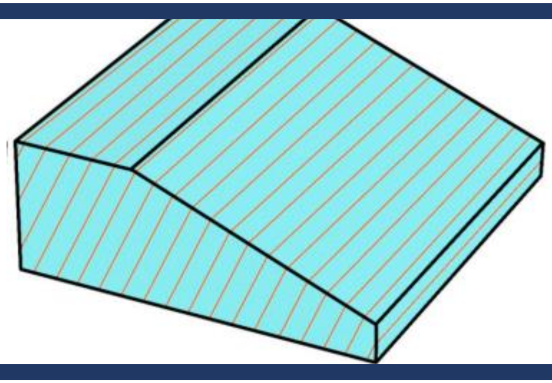


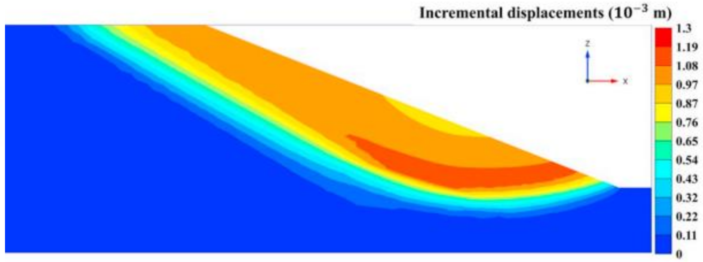
(c)

θ >slope angle
(cataclinal slope)



(c)





(d)

The failure surfaces of the two conditions (c) and (d) are generally deeper then (a) and (b).

Conclusions

Conclusions

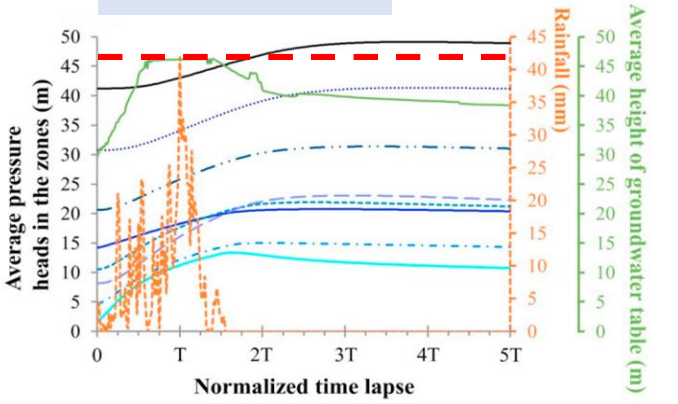
The three-dimensional analysis enables the comparison of the factors of safety among cataclinal, orthoclinal, and anaclinal slopes during rainfall and also the comparison of different dip angle of bedding plane.

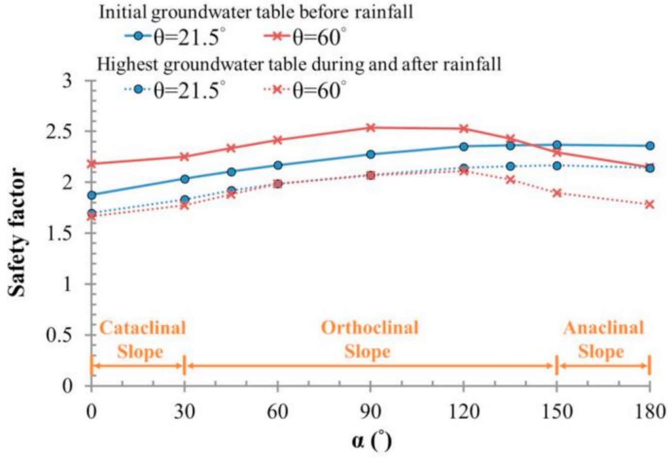
During and after rainfall, a slope with steeply dipping bedding planes exhibits a greater rise of the groundwater table and greater increase of pore water pressure, resulting in a larger reduction in the factor of safety than that with gently dipping bedding planes.

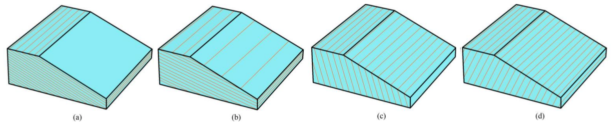
The unfavorable bedding plane-slope conditions for slope stability

Note that in addition to the orientation of bedding planes, the calculated values were affected by the rainfall condition, strength characteristics, hydraulic characteristics and slope geometry as well.

$\alpha = 0\ ;\ \theta = 60°$







Thanks you for your attention!