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The effect of hydrothermal alteration of the host rock mass on the slope stability of an open pit mine at Tujuh Bukit, East Java

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Abstract

Tujuh Bukit (BSI), located in East Java, Indonesia, is an open pit gold mining operation by PT Bumi Suksesindo, a wholly owned subsidiary of PT Merdeka Copper Gold. Slope instability is a significant problem often arising in open pit mining. The Tujuh Bukit mine is experiencing some instability due to variability in the rock mass geotechnical characterisation. The rock mass geological character, which has an igneous origin with a hydrothermal alteration undertone, appears to have changed the rock mass behaviour.

Hydrothermal alteration can change the physical and mechanical properties of the original rock mass. This modified condition is not always sufficiently considered in the design of open pit mines. With exposure to the elements, the rock mass deteriorates rapidly and the pit slopes become unstable and difficult to manage.

For this reason it is necessary to carry out detailed geotechnical investigations and laboratory testing to determine if the rock mass alteration is likely to have a destabilising effect. It requires detailed planning and diligence to ensure additional core samples are collected during the geotechnical drilling program and investigation.

A point load index (PLI) testing program was carried out on core samples in the laboratory to determine the hardness change for each of the lithologies. This data was obtained to support the slope stability analysis modelling.

This paper shows that it is necessary to determine the presence of hydrothermal alteration as it appears to have a strong influence on slope instability. It was further necessary to isolate the occurrence and the type of alteration within the geotechnical model by assigning rock mass zoning codes based on the variability of the rock strength for each type of alteration as the effect can greatly affect the rock mass strength.

Keywords: *hydrothermal alteration, point load index, slope stability, open pit mine*

1 Introduction

The Tujuh Bukit mine is one of PT Merdeka Copper Gold's Indonesian gold mining enterprises that use the open pit mining method. Slope stability analysis is required as part of the open pit method incorporating slope design as a critical control for active mining and post-mining stages. Figure 1 shows the location of the study area.

Figure 1 Location of the Tujuh Bukit mine, East Java

The gold is produced using a typical leaching method, where the crushed ore is stacked on an impermeable geosynthetic membrane liner to prevent contamination. The ore is then irrigated using a chemical solution to dissolve the desired metal into a solution which flows towards the base of the stacked ore on top of the impermeable liner where the leachate (pregnant solution) is collected at various points. The irrigation process is carried out over a set frequency to fit in with the planned production cycle.

The open pit mining method is experiencing some degree of slope instability which appears to be influenced by geological and rock mass strength variability throughout the mining lease area. This rock mass strength variability appears to be caused by hydrothermal alteration within the various lithological units, which is described in the section below.

2 Geological background and the underlying problem

Volcanic rocks, including volcanic breccias and tuff, dominate the lithology of the formations within this mining lease research area. Sandstone and andesitic lava lithology inclusion are also present within this deposit. The majority of the lithology that makes up this formation exhibits substantial alteration characteristics, which is a sign of nearby hydrothermal activity. Mineralised host rocks are also found in this geological formation.

The type of alteration, regional and local geological structure, and the presence of high rainfall all have an impact on the slope stability that frequently occurs in the study area.

High intensity rainfall, a tropical climate, an elevated weathering process and erosion from surface water runoff are all additional factors causing slope instability.

Rock mass characterisation variability, the presence of geological structures and groundwater behind the pit walls (currently the subject of an investigation) appear to have an impact on rock mass quality (e.g. contributing to poor rock mass).

Geological processes that occurred during and after rock formation also appear to influence the rock mass engineering properties. The Tujuh Bukit mine operational area experienced historical failure of the pit slopes (Figure 2). These unstable areas all exhibit different igneous rock mass characteristics and appear to have been weakened, thus having the potential to continue to adversely affect the slope's stability and become a planning and mine operation problem.

Figure 2 Historical failure of the pit slope

Read & Stacey (2009) highlight this phenomenon that causes potential over and/or undercutting in pit slopes, resulting in mine pit slopes being less stable and therefore requiring mine designs to be more sophisticated in incorporating rock mass variability as part of the planning and design process.

The bench scale instability warrants some background research on the topic of rock mass variability and its potential impact on slope stability. It therefore dictated the use of a well-known model describing a process to follow in identifying and showcasing the variability in rock mass strength (Figure 3).

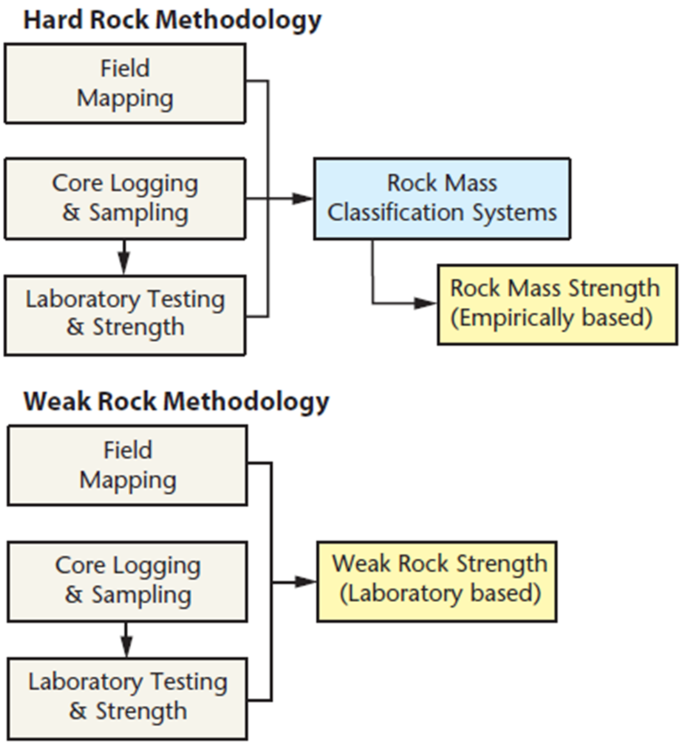


Figure 3 Comparison of methodologies used to establish the strength of strong and weak tock (Martin & Stacey 2018)

3 Field data collection and laboratory test program

Geotechnical data was obtained from available drill cores during the 2019 to 2022 exploration drilling program. In addition, supplementary pit mapping data, based on the updated condition of the open pit slope wall, have been used to correlate the rock mass alteration logged in the drillholes.

Figure 4 below shows the study area and locations within the pit where core and surface samples were collected from the boreholes and batters respectively. The red dots are samples taken from borehole data, while the blue dots are samples taken from surface data. The yellow line is the pit boundary design.

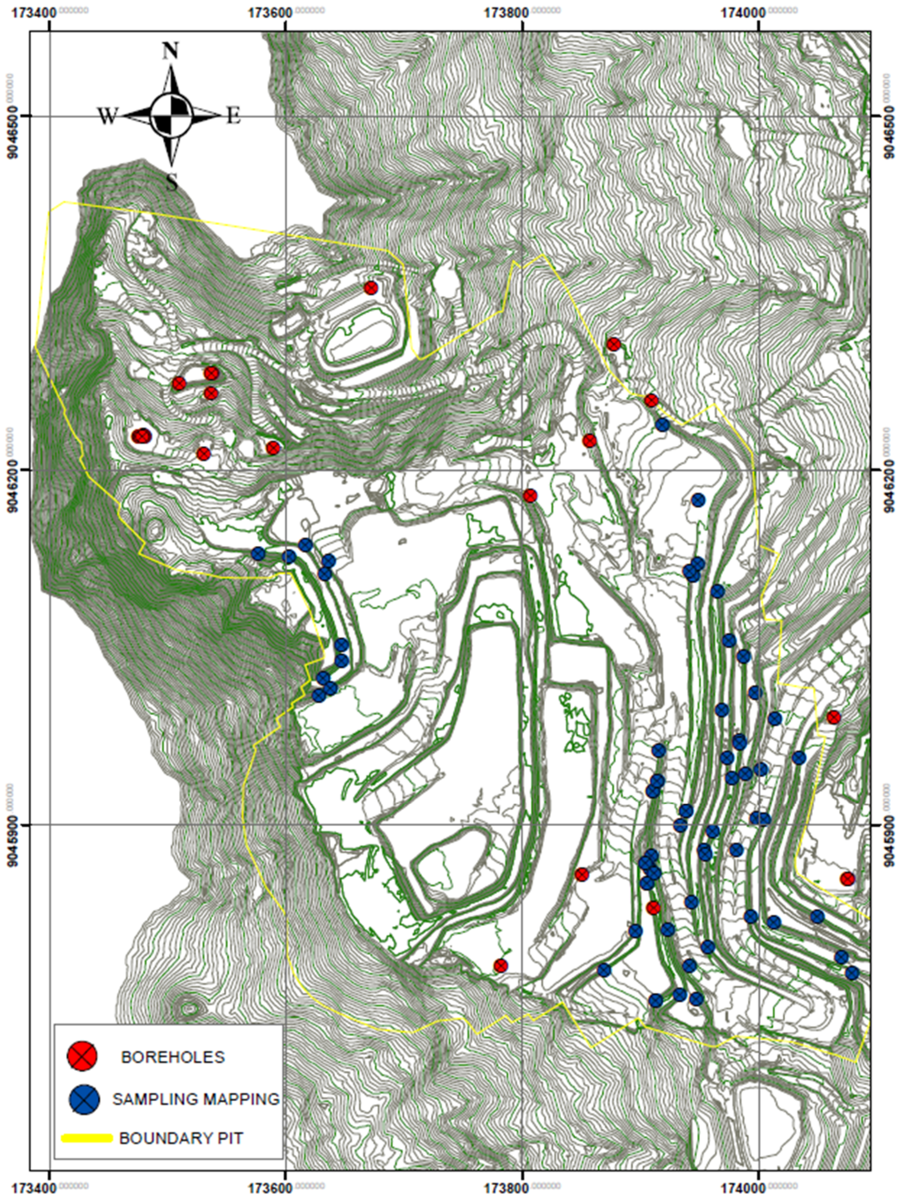


Figure 4 Location of rock alteration sampling from boreholes and surface samples

Laboratory tests on rock core specimens which include the point load strength index (PLI) test and unconfined compressive strength (UCS) data were adopted as the basis to determine the variability in rock mass strength for each of the rock alteration type. Table 1 below highlights the alteration and mineralogy variability within the rock mass.

Table 1 Alteration type description

Abbreviation	Alteration type	Description
AR	Advanced argillic	Laoline, quartz
C-Ca	Propylitic	Chlorite calcite
CC	Argillic	Clay, chlorite
Hcy	Argillic	Kaolinite-alunite
Hcy-si	Argillic	Kaolinite-silica
Hsi	Massive silica	Silica and quartz
Hsi-al	Silica alunite	Silica and alunite
Hsi-cy	Advanced argillic	Kaolinite, quartz and alunite
Hsi- cy + al	Silica alunite	Silica, clay and alunite
IA	Intermediate argillic	Smectite, illite and kaolinite
Pro/PRO	Propylitic	Chlorite and epidote

Figure 5 shows the distribution of rock alteration minerals identified in samples collected during surface mapping efforts and samples obtained from core being drilled by the Tujuh Bukit geoscience team. The samples were tested adopting the PLI test to determine an Is_{50} strength value.

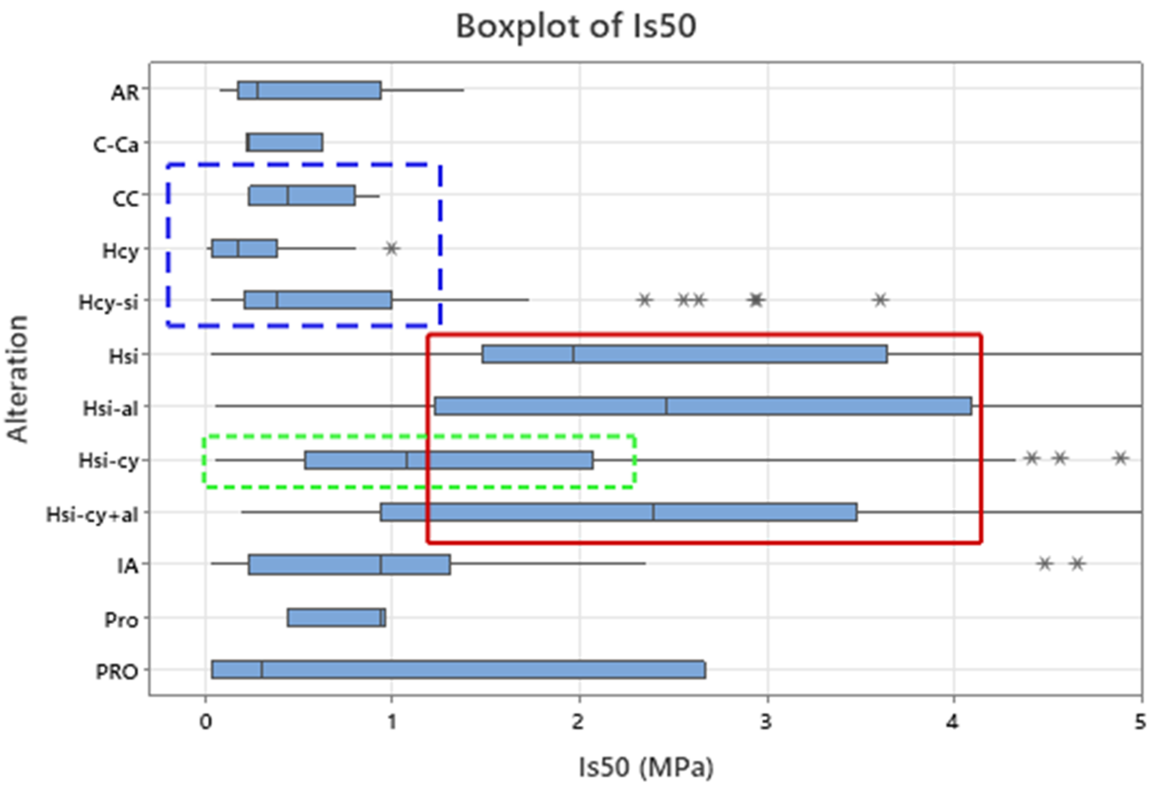


Figure 5 Distribution of rock alteration mineral versus PLI test (Is50) results

Figure 6 shows the distribution of rock alteration and UCS (in MPa) that has been simplified by only including three types of alteration – Hcy-Na (argillic), Hcy-Ka (advanced argillic) and Hsi-Al (silica alunite) – that occur in the high-sulphidation zone (host rock – main composition of the pit slope walls).

The point load index test findings, which were taken into consideration when classifying the alteration rock mass strength variability, were used to determine and correlate the UCS results such that each rock alteration (modification) yields the rock's strength.

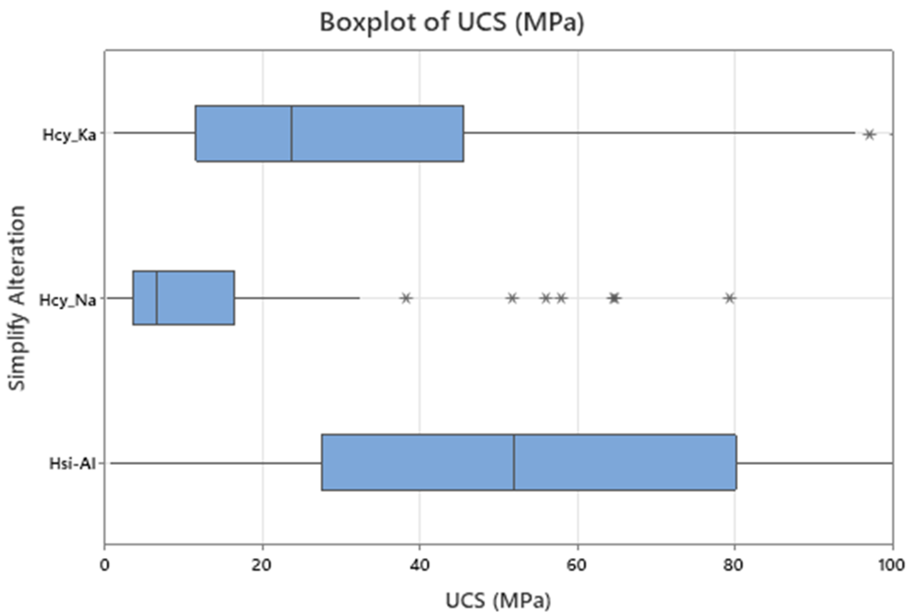
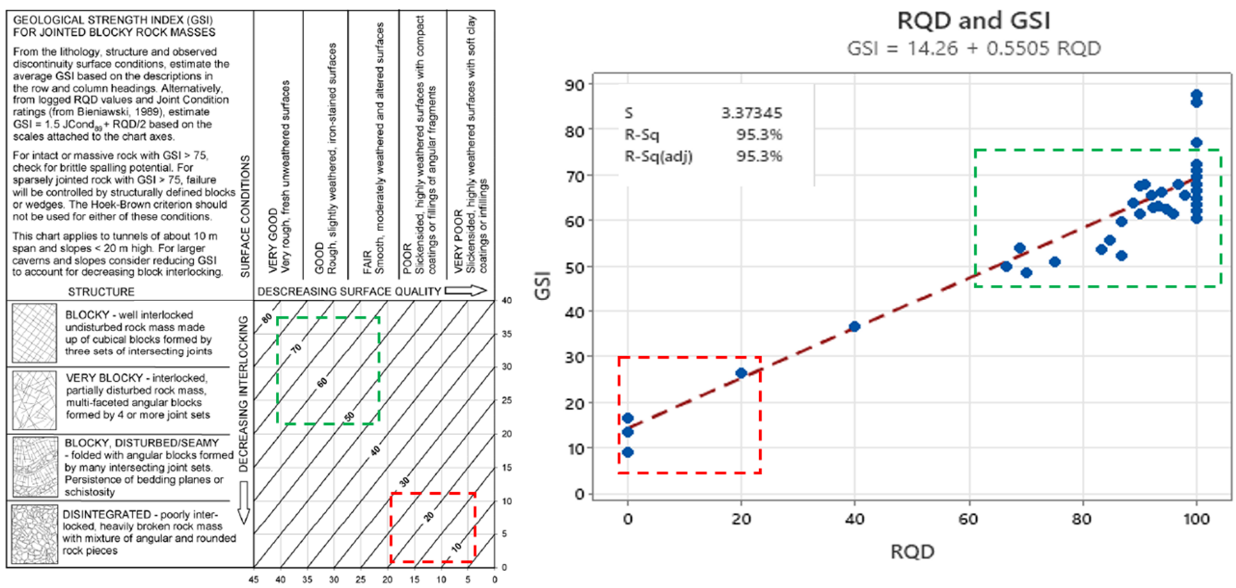


Figure 6 Simplified rock alteration type versus strength or UCS (MPa)

Figure 7 shows the geological strength index (GSI) and rock quality designation (RQD) relationship. GSI quantification is based on RQD and joint conditions (Hoek et al. 2013). The GSI data coverage was considered adequate to evaluate the local zone with various rock mass strengths.



(a) (b)

Figure 7 (a) Quantification of geological strength index (GSI) by joint condition and rock quality designation (RQD); (b) RQD and GSI relationship (Hoek et al. 2013)

4 Material properties

Following on from the above, the rock strength characteristics of the alteration have been simplified into three types, namely argillic alteration, advanced argillic and silica alunite obtained from rock samples from drilling and surface sampling. Samples were tested in the rock mechanics laboratory using the PLI test. These data results were correlated with the UCS using the Is_{50} convention with range of 21–24 for samples with a diameter of 50 mm (Bieniawski 1975):

$$UCS = 22\ x\ I_{S^{50}} \tag{1}$$

The additional data incorporated as part of the study was the rock mass quality, found by measuring the core defect condition from the core drilling data using the RQD relationship to determine the GSI using the Hoek et al. (2013) relationship:

$$GSI = 1 + \frac{RQD}{2} + 1.5JCond_{89} \tag{2}$$

where $JCond_{89}$ is estimated for joint alteration, friction and weathering.

Thus the results from the data correlation have been established from the GSI value for the rock alteration type. The results of these values are provided in Table 2, incorporating Bieniawski's (1989) rock mass rating criteria.

Table 2 Rock mass parameters – generalised Hoek–Brown criterion

Hydrothermal alteration	Unit weight (kN/m^3)	RMR_{89}	GSI	UCS (Mpa)	m_i	D	Rock mass elasticity modulus (Gpa)	Poisson's ratio
Hcy-Ka (advanced argillic)	21	49–55	48–58	11–45	15	0.7	3.558	0.3
Hcy-Na (argillic)	21	46–50	25–40	3–16	13	0.7	0.340	0.3
Hsi-Al (silica alunite alteration)	27	61–65	60–72	28–80	19	0.7	5.308	0.3

RMR_{89} = rock mass rating; GSI = geological strength index; UCS = unconfined compressive strength

The aim of highlighting the rock mass classification has a dual purpose:

- Showcasing rock mass variability.
- Using the classification system to downgrade the rock mass strength and modulus within the finite element analysis.

5 Slope stability analysis comparison

- The slope stability assessment was conducted using the limit equilibrium method (Slide 2D) and finite element method (RS2) from Rocscience (2023). The shear strength reduction RS 2 method and Factor of Safety (FoS) stability refers to the ability of a slope to resist force that drives material down the slope. The strength reduction factor (SRF) is equivalent to the safety factor of the slope.The strength parameters of a slope are reduced by a certain SRF, and the finite element stress analysis is computed.
- This process is repeated for different values of SRF until the model becomes unstable (the analysis results do not converge).
- This determines the critical SRF, or FoS, of the slope.

Some analysis considerations follow:

- Slope stability analysis comparison is considered for three types of rock alteration as shown in Figures 8 to 19 for FoS and SRF.
- The analytical model uses both dry and wet conditions for every parameter and alteration.
- Pseudo-static condition was considered for the model design parameters (i.e. peak ground accelerations) considered with 0.33 g for Operating Basis Earthquake and Maximum Design Earthquake respectively (Knight Piesold Consulting 2022).
- Current open pit dimensions – bench height = 15 m, bench width = 7.7 m and bench face angle = 75° for hydrothermal silica alteration; and bench height = 7.5 m, bench width = 4.8 m and bench face angle = 65° for hydrothermal clay alteration.

Section 5.1 is a brief overview of the limit equilibrium and finite element numerical analysis models used to showcase the weakening effect of the alteration within the rock mass.

5.1 Slope stability analysis comparison – models

The following models were set up to assess and compare the impact of the different representative rock mass alterations (i.e. perceived weakened rock mass) and are displayed in the section below:

- A.1 Argillic saturated and dry condition (static and pseudo-static – limit equilibrium analysis – see Figures 8–9).
- A.2 Argillic saturated and dry condition (static and pseudo-static – finite element analysis – see Figures 10-11).
- B.1 Advanced argillic saturated and dry condition (static and pseudo-static – limit equilibrium analysis – see Figures 12–13).
- B.2 Advanced argillic saturated and dry condition (static and pseudo-static – finite element analysis – see Figures 14–15).
- C.1 Advanced argillic saturated and dry condition (static and pseudo-static – limit equilibrium analysis – see Figures 16–17).
- C.2 Silica alunite saturated and dry condition (static and pseudo-static – finite element analysis – see Figures 18–19).

A.1 Argillic saturated and dry condition (static and pseudo-static – limit equilibrium analysis)

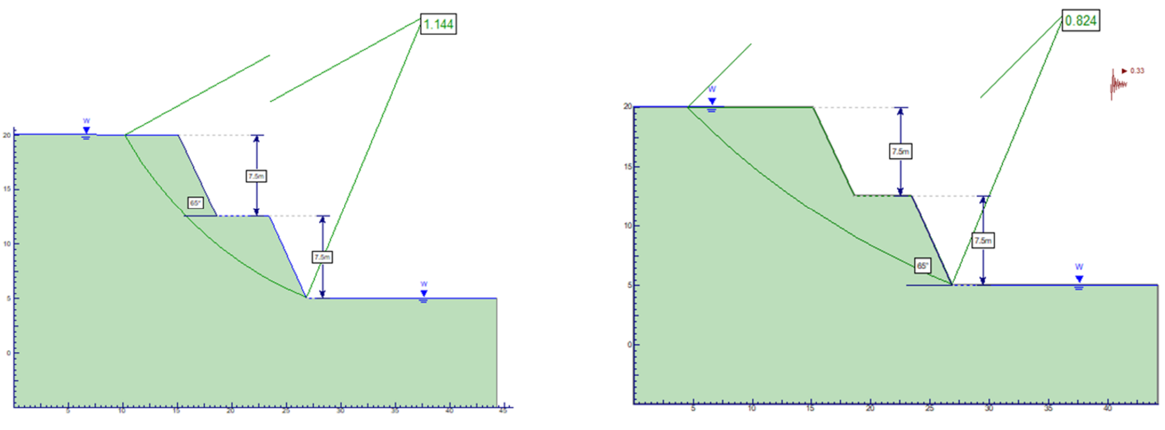
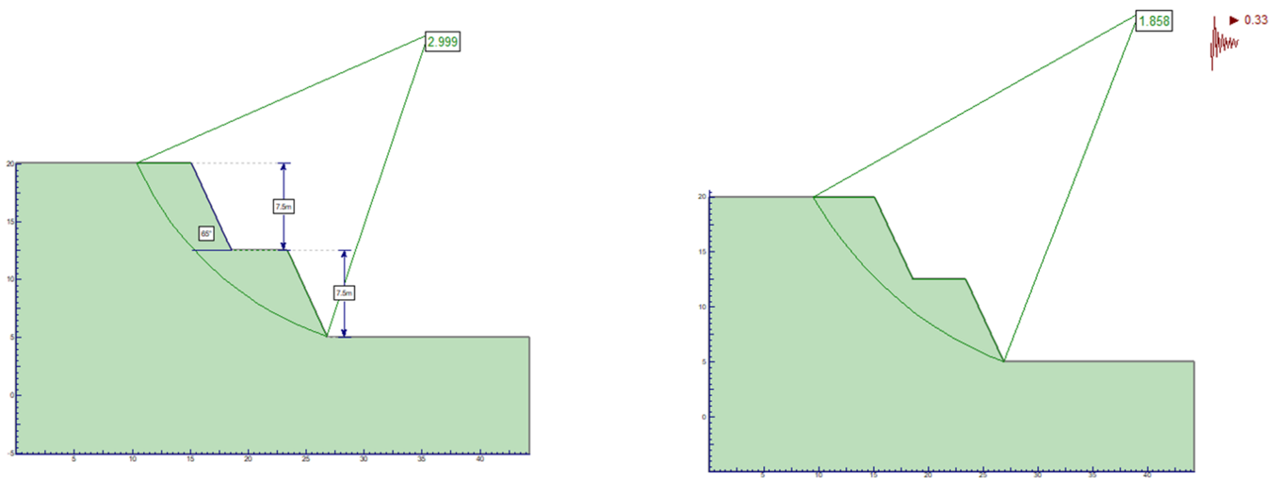


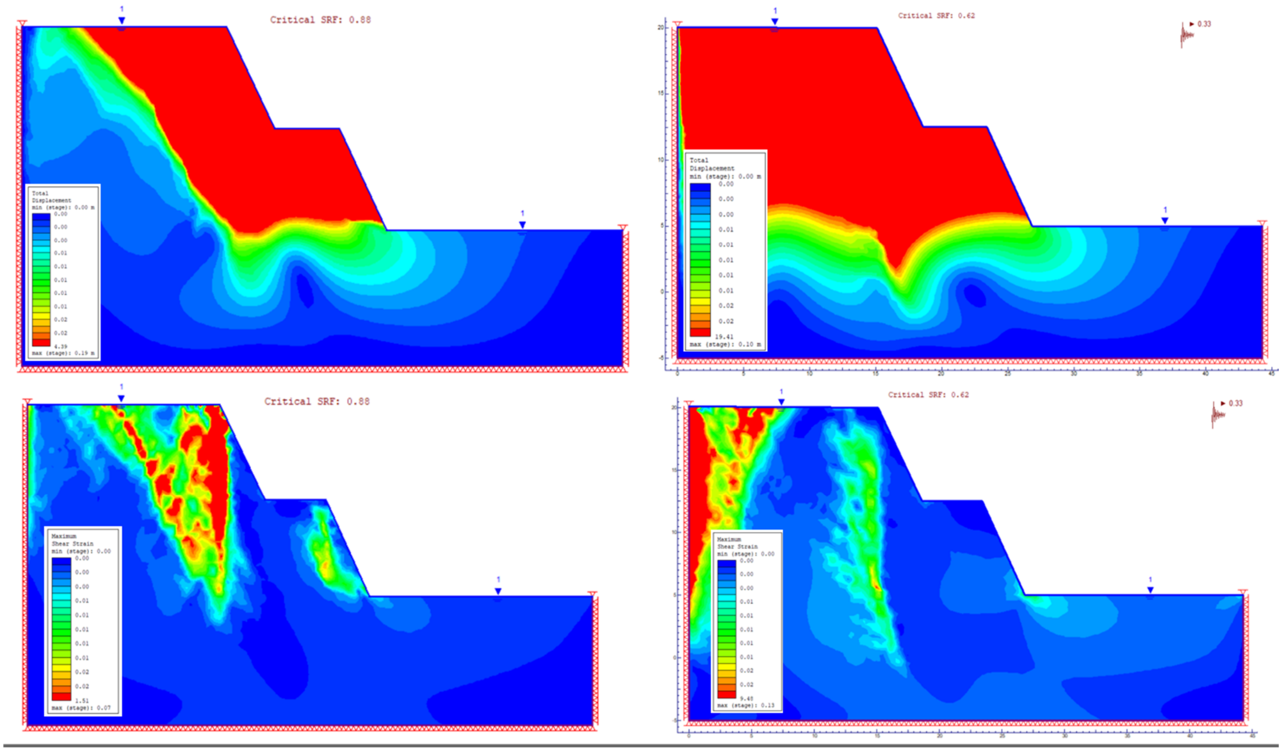
Figure 8 (a) Factor of Safety (FoS) of argillic saturated with static condition (by limit equilibrium method); (b) FoS of argillic saturated with pseudo-static condition (by limit equilibrium method)



(a) (b)

Figure 9 (a) Factor of Safety (FoS) of argillic dry with static condition (by limit equilibrium method); (b) FoS of argillic dry with pseudo-static condition (by limit equilibrium method)

A.2 Argillic saturated and dry condition (static and pseudo-static – finite element analysis)



(a) (b)

Figure 10 (a) Factor of Safety (FoS) of argillic saturated with static condition by shear reduction factor (SRF) method; (b) FoS of argillic saturated with pseudo-static condition (by SRF method)

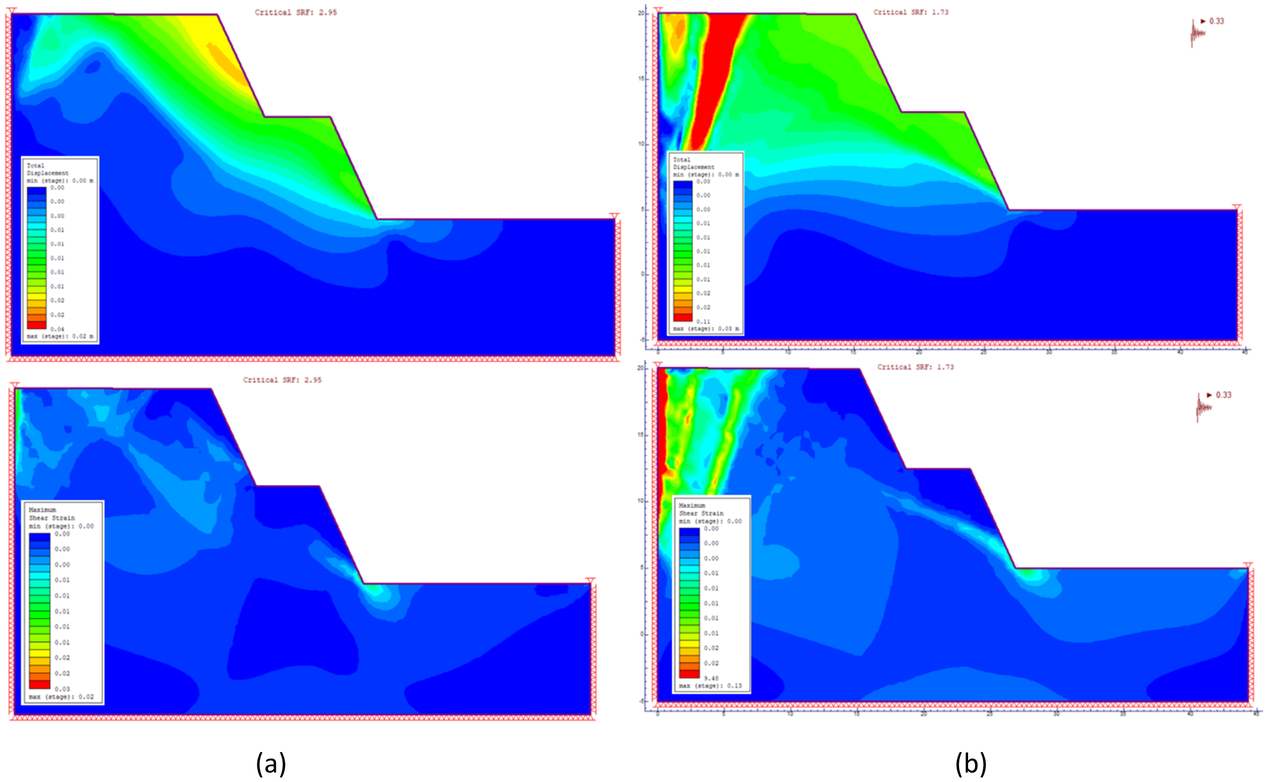


Figure 11 **(a) Factor of Safety (FoS) of argillic dry with static condition by shear reduction factor (SRF) method; (b) FoS of argillic dry with pseudo-static condition by SRF method**

B.1 Advanced argillic saturated and dry condition (static and pseudo-static – limit equilibrium analysis)

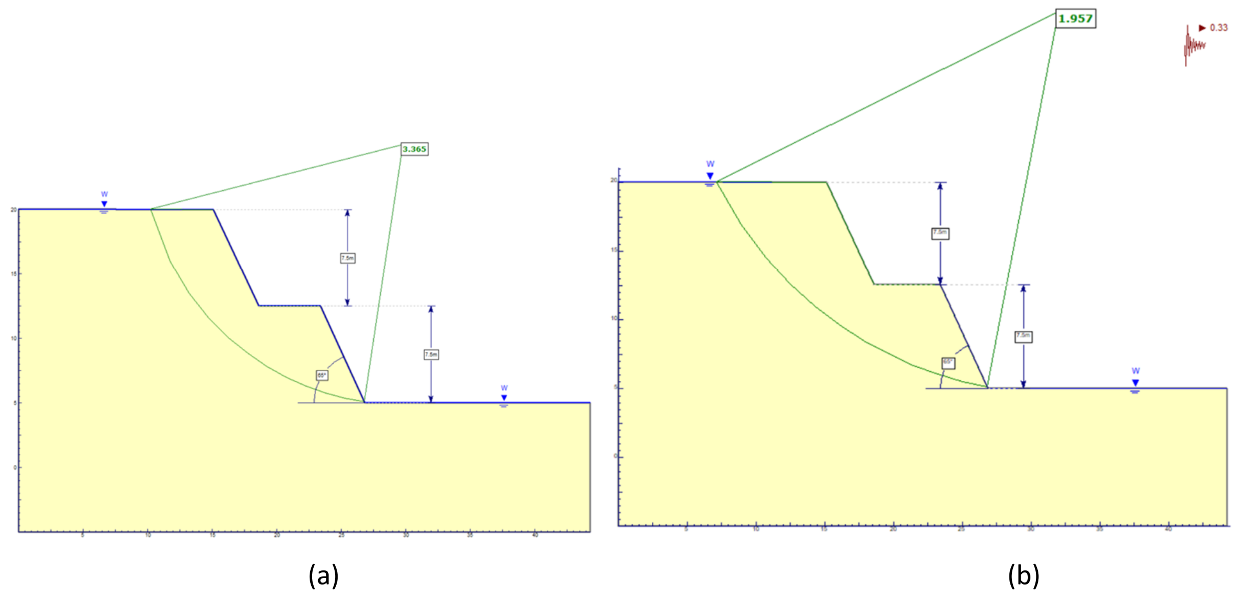
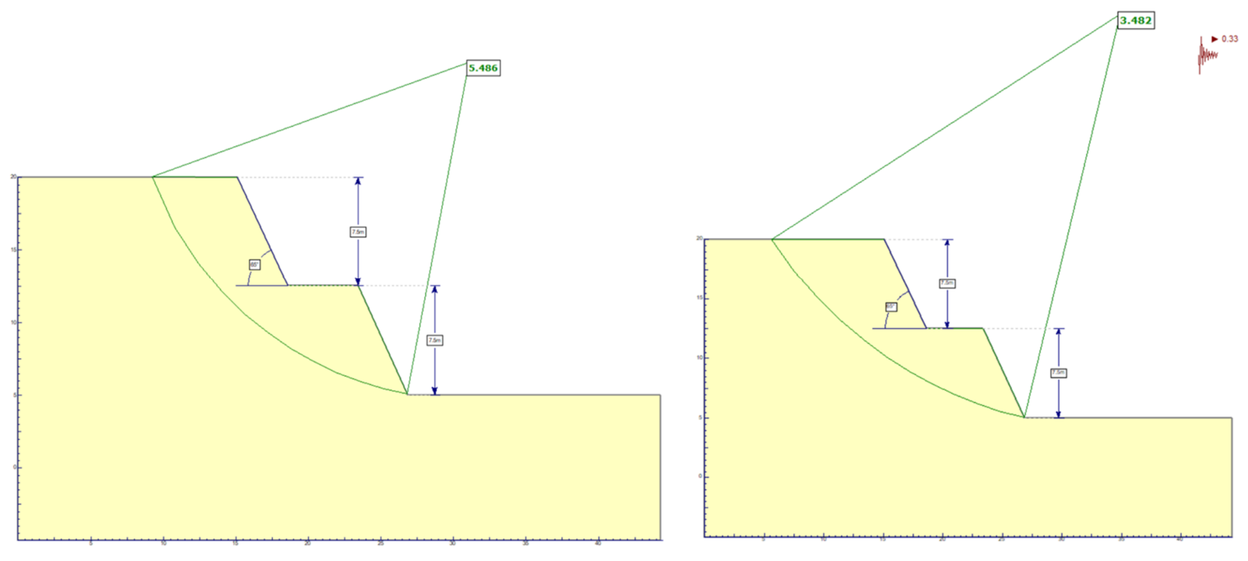


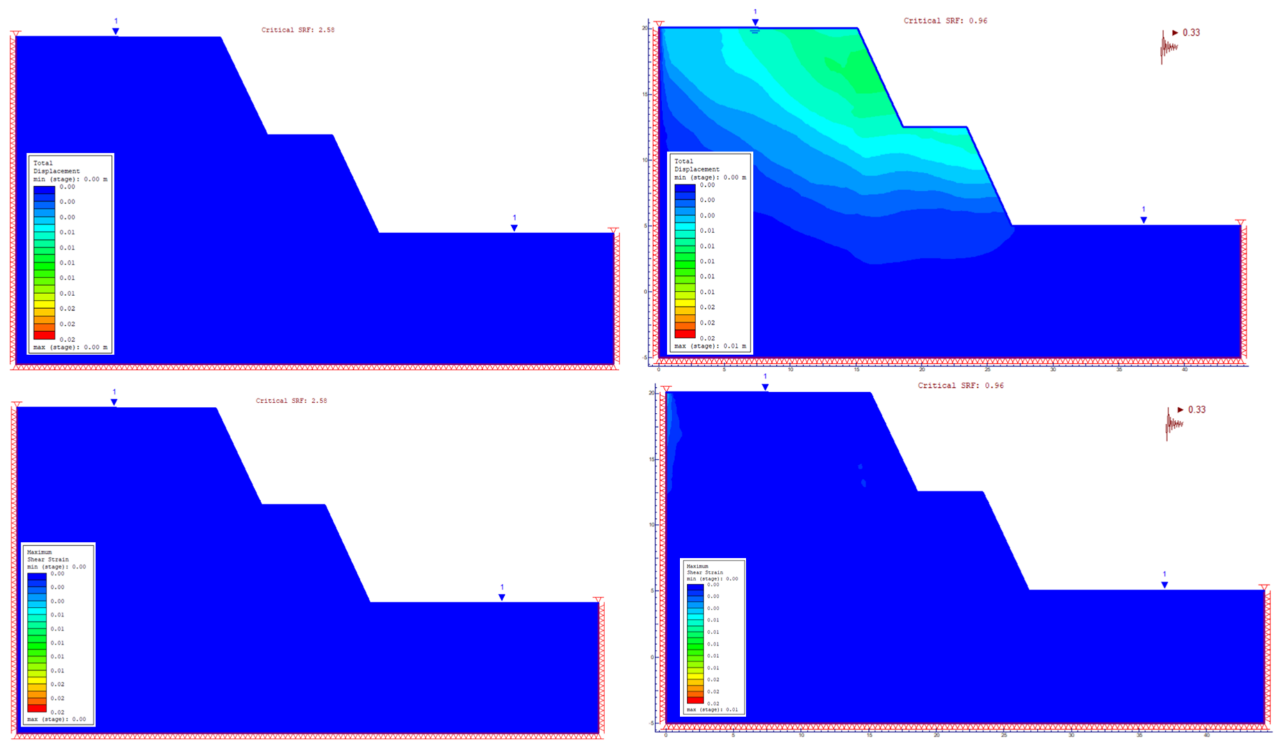
Figure 12 **(a) Factor of Safety (FoS) of advanced argillic saturated with static condition by limit equilibrium method; (b) FoS of advanced argillic saturated with pseudo-static condition by limit equilibrium method**



(a) (b)

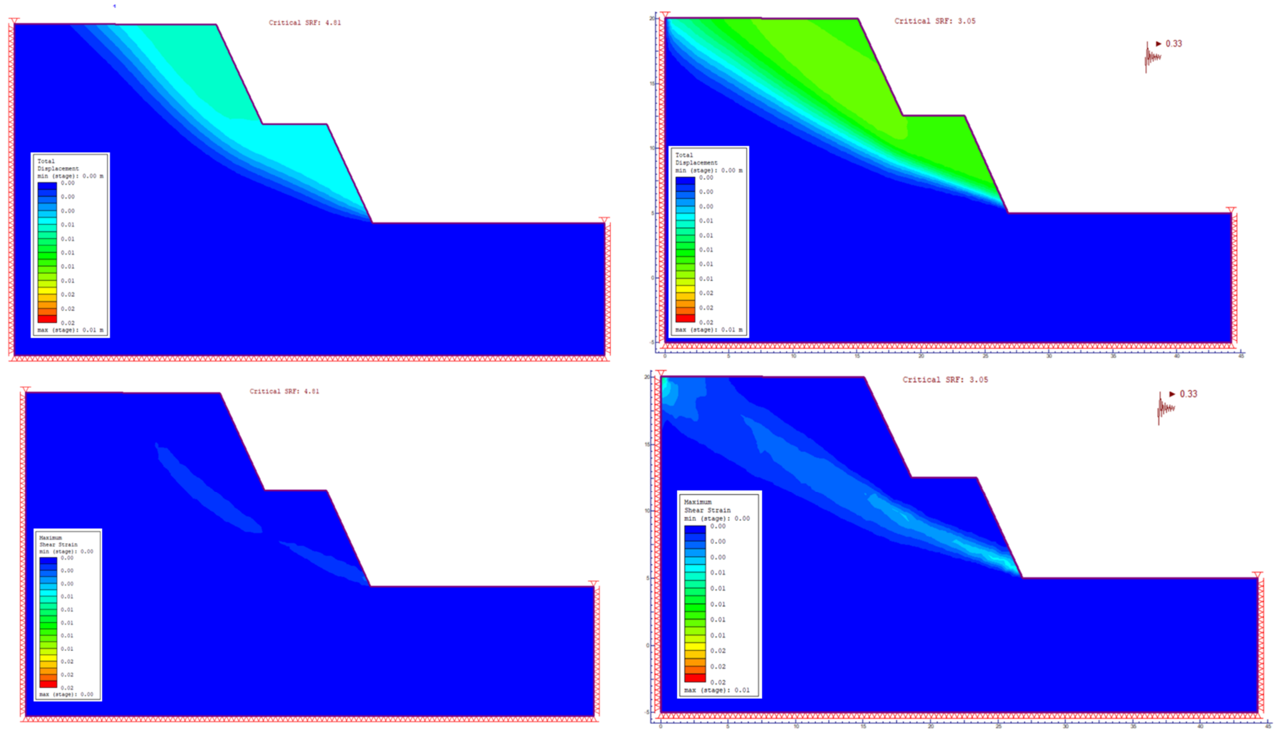
Figure 13 **(a) Factor of Safety (FoS) of advanced argillic dry with static condition by limit equilibrium method; (b) FoS of advanced argillic dry with pseudo-static condition by limit equilibrium method**

B.2 Advanced argillic saturated and dry condition (static and pseudo-static – finite element analysis)



(a) (b)

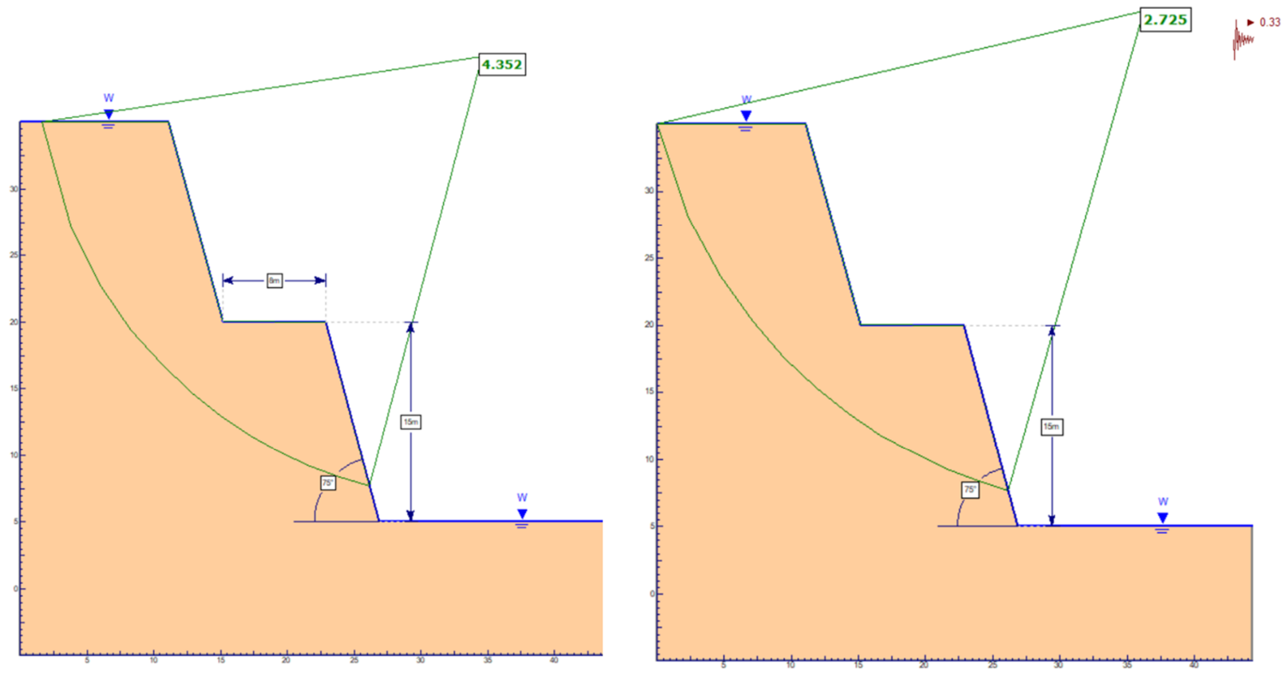
Figure 14 **(a) Factor of Safety (FoS) of advanced argillic saturated with static condition by shear reduction factor (SRF) method; (b) FoS of advanced argillic saturated with pseudo-static condition by SRF method**



(a) (b)

Figure 15 **(a) Factor of Safety (FoS) of advanced argillic dry with static condition by shear reduction factor (SRF) method; (b) FoS of advanced argillic dry with pseudo-static condition by SRF method**

C.1 Silica alunite saturated and dry condition (static and pseudo-static – limit equilibrium analysis)



(a) (b)

Figure 16 **(a) Factor of Safety (FoS) of silica alunite saturated with static condition by limit equilibrium method; (b) FoS of advanced argillic saturated with pseudo-static condition by limit equilibrium method**

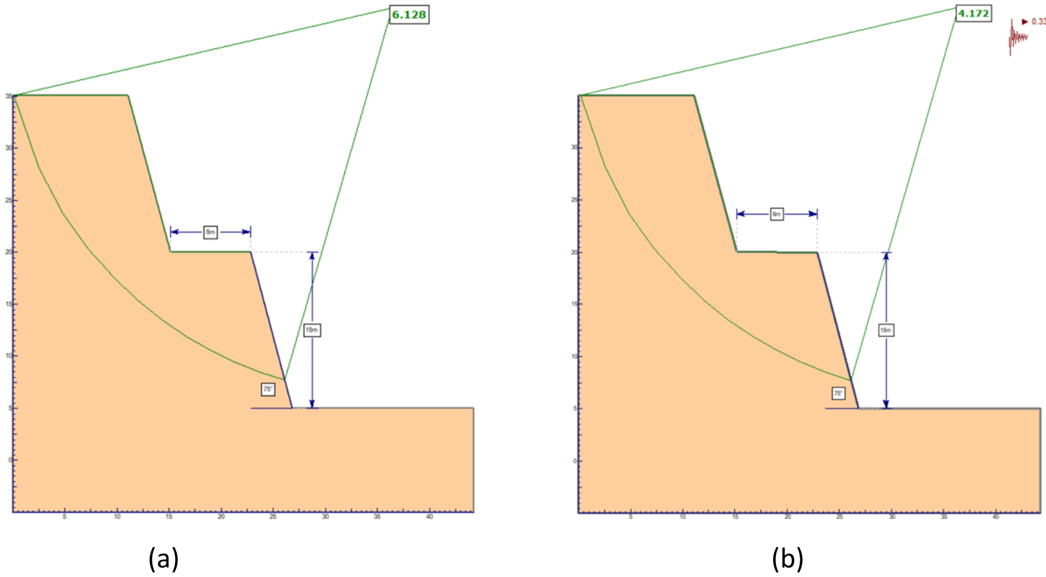


Figure 17 (a) Factor of Safety (FoS) of silica alunite dry with static condition by limit equilibrium method; (b) FoS of silica alunite dry with pseudo-static condition by limit equilibrium method

C.2 Silica alunite saturated and dry condition (static and pseudo-static – finite element analysis)

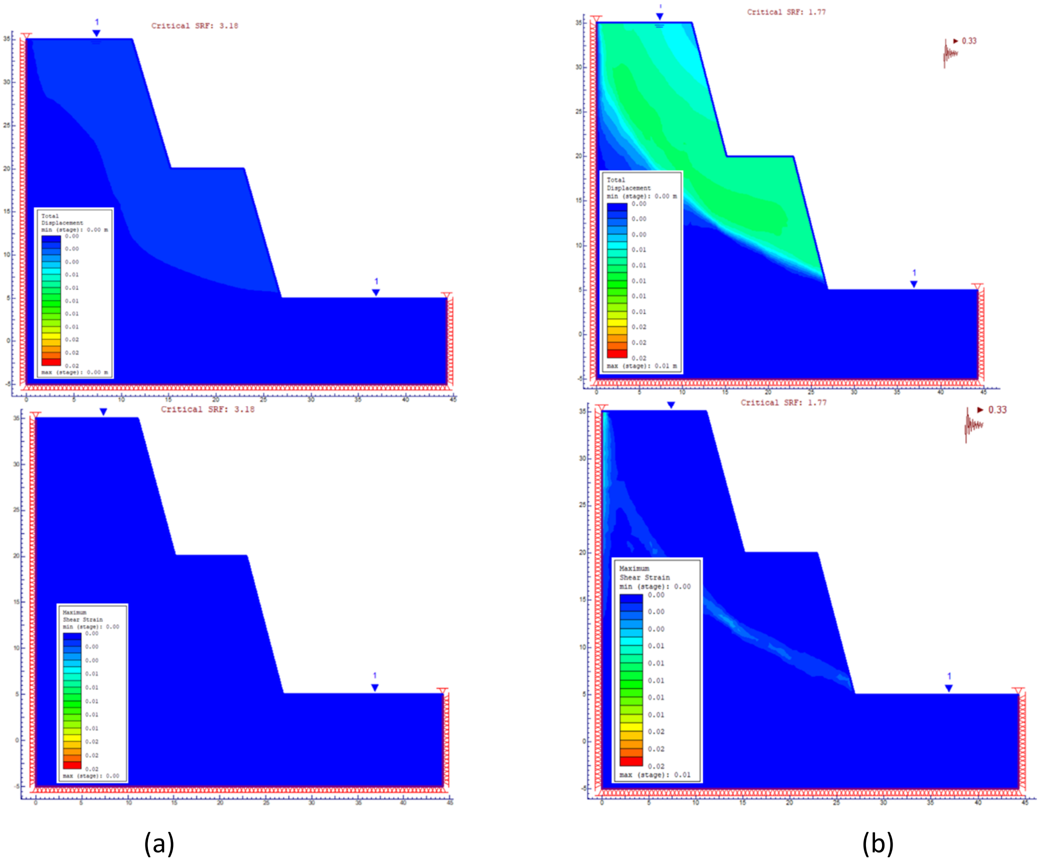
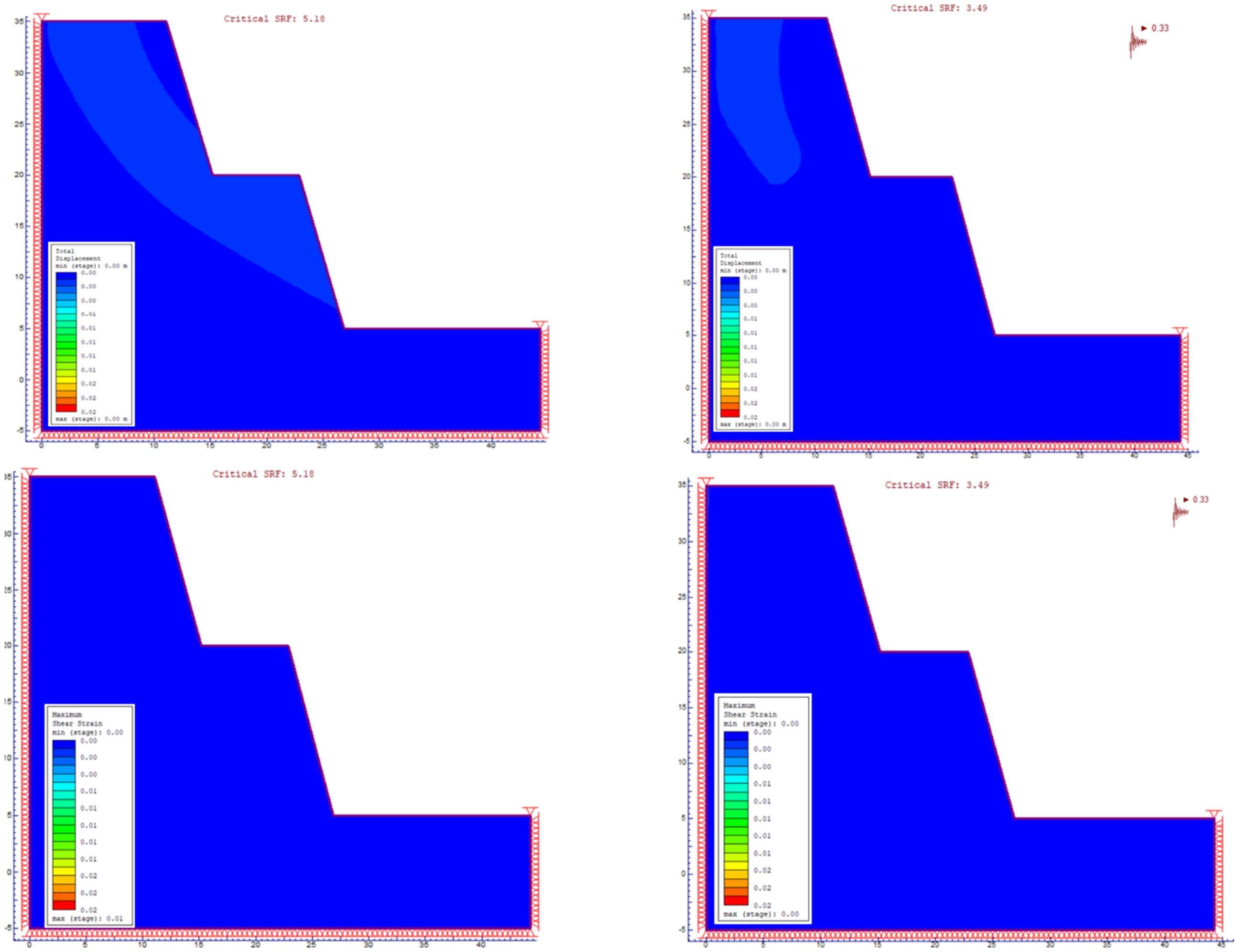


Figure 18 (a) Factor of Safety (FoS) of silica alunite saturated with static condition by shear reduction factor (SRF) method; (b) FoS of silica alunite saturated with pseudo-static condition by SRF method



(a) (b)

Figure 19 (a) Factor of Safety (FoS) of silica alunite dry with static condition by shear reduction factor (SRF) method; (b) FoS of silica alunite dry with pseudo-static condition by SRF method

Table 3 is a summary of the limit equilibrium and finite element numerical analysis results from above.

Table 3 Results of Factor of Safety (FoS) and shear reduction factor (SRF)

No.	material	FoS				SRF				Maximum displacement (cm)
		Static		Pseudo-static		Static		Pseudo-static		
		Dry	Saturated	Dry	Saturated	Dry	Saturated	Dry	Saturated	
1	Argillic alteration	2.9	1.1	1.8	0.8	3.0	0.9	1.7	0.6	19
2	Advanced argillic alteration	5.4	3.3	3.4	1.9	4.8	2.5	3.0	0.9	10
3	Silica alunite alteration	6.1	4.3	4.1	2.7	5.1	3.1	3.4	1.7	10

6 Conclusion

The results of the numerical analysis using the limit equilibrium and SRF methods varied for the three types of rock alteration. Of the three alteration types, the argillic type is expected to have the lowest level of stability of the three types analysed. This type of argillic alteration strength, when subjected to saturated conditions, will be greatly affected as observed in the analysis and from historical failures in the pit (see Figure 7a). Accordingly, the impact of water on the argillic alteration type material in the pit wall is very strong.

Thus surface water runoff management is key to maintaining slope stability in the open pit at Tujuh Bukit. A groundwater investigation is underway to determine rock mass permeability in order to understand the process of groundwater recharge, the dissipation rate and the rate of rock mass deterioration. The result of this work may indicate the requirement for groundwater dissipation and/or depressurisation.

To ensure the accuracy of the data used to determine the strength of the altered rock in the host rock and pit wall zone it is necessary to carry out additional detailed geotechnical investigations to identify the distribution of the alteration types and the strength of the altered rocks. The authors recommend an alteration model refinement by means of geological alteration block modelling, which can further be used as a means to define or understand the risk and also to conduct more sophisticated 3D stress versus (shear) strain numerical analysis.

Historical data can also be used as back-analysis to determine material property values. Alteration rocks within the host rock are varied and, as described, have different physical properties. Thus it is necessary to update the geotechnical strength data on a regular basis because the environment and presence of the alteration rock types greatly affect the stability of the slopes.

It is recommended to have a geotechnical hazard map indicating areas where the host rock has been affected by alteration, and a geotechnical strategic monitoring plan established for areas with this type of geotechnical risk.

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