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Impact of Groundwater Table Fluctuation on Stability of Jointed Rock Slopes and Landslides

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Abstract: Groundwater level plays an important role in triggering landslides. In this paper, Distinct Element Method is used to investigate the impact of groundwater table fluctuation on the stability of jointed rock slopes. For this purpose, 110 cases including different number of joint sets, joint friction angles, joint spacings, and joint angles are considered and the influence of changing groundwater level on the stability of a jointed rock slope is investigated through a series of parametric studies. This study shows that the factor of safety for slopes can decrease significantly with increasing the groundwater level, and the impact is more significant on slopes with steeper joints. Furthermore, as the spacing of the joints decreases, the impact decreases. However, as the joint spacing increases, the groundwater table should rise to a higher elevation to be able to have an impact. Moreover, the impact on the factor of safety is similar for different joint friction angles when the groundwater level elevation is high. This study provides a better understanding of the impact of groundwater table fluctuation on the stability of jointed rock slopes.

Keywords: landslide; jointed rock slope; groundwater table; slope stability analysis; distinct element method



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1. Introduction

Landslides, as one of the most well-known and frequent hazards on Earth, can cause loss of life, serious destruction of infrastructure and severe damage to property [1–3]. Therefore, prediction of landslides and reliable slope design in geotechnical, civil and mining projects can not only improve safety but also avoid unexpected significant costs due to slope failure [4]. There are different methods for slope stability analysis: Limit Equilibrium Method [5–7]. Limit Analysis Method [8–10]; Numerical Modeling Method [11–13]. Numerical methods used to analyze slopes are usually the Finite Difference Method (FDM) [14,15], Finite Element Method (FEM) [16], Discrete Element Method [17] and Distinct Element Method [18,19] (both known as DEM), Discontinuous Deformation Analysis (DDA) [20,21] and Discrete Fracture Network (DFN) [22]. DEM, DDA and DFN are the most suitable methods for stability analysis of jointed rock slopes because they simulate the discontinuum behavior of rock masses by considering rock blocks and discontinuities [23–29].

The groundwater level has a significant effect on slope stability and landslide development [30–33] and the groundwater table could fluctuate because of the influence of rainfall infiltration, pumping, tides, and other reasons ([34,35]). Therefore, it is essential to have a good understanding of how groundwater table fluctuations affect the stability of slopes.

Although there are many papers on the effect of groundwater on slope stability, to date there is no parametric study published on investigating the impact of groundwater table fluctuation on the stability of jointed rock slopes. For instance, Beyabanaki et al. [36] investigated the impact of groundwater table position, soil strength properties and rainfall on instability in relation to earthquake-triggered landslides. Ray et al. [37] studied the effects of unsaturated zone soil moisture and groundwater table on slope instability. Song et al. [38,39] investigated the influence of a rapid water drawdown on the seismic response characteristics of reservoir rock slopes. Xue et al. [40] investigated the stability

analysis of loess slopes with a rising groundwater level. Sun et al. [41] studied the influence of water–rock interaction on the stability of Schist Slopes. Finally, Xu et al. [42] studied the influence of reservoir water level variations on the stability of slopes near the reservoir banks. However, no parametric study of joint parameters was carried out in these investigations.

In this paper, Distinct Element Method is used to investigate the impact of groundwater table fluctuation on the stability of jointed rock slopes through a series of parametric studies. For this purpose, different number of joint sets, joint friction angles, joint spacings, and joint angles are considered and the effect of changing groundwater level on the stability of a jointed rock slope is studied.

2. Distinct Element Method

Rock masses are represented as assemblies of discrete blocks in DEM. Joints are considered as interfaces between distinct blocks. A series of calculations that trace the movements of the blocks, caused by applied loads or body forces, are performed to obtain the contact forces and displacements at the interfaces of a stressed assembly of blocks. The DEM calculations are based on application of a force displacement law in order to find contact forces from known displacements, at all contacts, and Newton's second law in order to find the motion of the blocks resulting from the known forces acting on them, at all blocks. If the blocks are not rigid, motion is calculated at the grid-points of the triangular finite-strain elements within the blocks [43].

The calculation for DEM is presented below. For more information, see [43].

$$F_n := F_n - k_n \Delta u_n \quad (1)$$

$$F_s := F_s - k_s \Delta u_s \quad (2)$$

$$F_i = \sum F_i^c \quad (3)$$

$$M = \sum e_{ij} x_i F_j \quad (4)$$

$$F_i^c = \int \sigma_{ij} n_j ds \quad (5)$$

$$F_i = F_i^e + F_i^c \quad (6)$$

$$F_i = F_i / m \quad (7)$$

$$t := t + \Delta t \quad (8)$$

where,

F_n = Normal force;

F_s = Shear force;

K_n = Normal stiffness;

K_s = Shear stiffness;

Δu_n = Normal displacement increment;

Δu_s = Shear displacement increment;

F_i = Resultant of all external forces;

F_i^c = Contact force;

e_{ij} = Strain;

M = Total moment acting on the block;

m = Mass;

x_i = Coordinates of block centroid;

σ_{ij} = Zone stress tensor;

n_j = Unit outward normal;

t = Time;

Δt = Time step.

For this study, a DEM software called Universal Distinct Element Code (UDEC) [43] is used. In UDEC, a fully coupled mechanical-hydraulic analysis is performed so that fracture conductivity is dependent on mechanical deformation and, conversely, joint fluid pressures affect the mechanical computations. The calculation for the fully coupled mechanical-hydraulic analysis in UDEC is presented below. For more information, see [43].

$$F_i = p n_i L \quad (9)$$

$$Q = -k_j a^3 \frac{\Delta p}{L} \quad (10)$$

$$a = a_0 + \Delta a \quad (11)$$

$$\Delta p = \frac{k_w}{V} \left\{ \sum Q \Delta t - \Delta V \right\} \quad (12)$$

where,

p = Pressure;

k_w = Bulk modulus of fluid;

a = Contact hydraulic aperture;

a_0 = Joint aperture at zero normal stress;

Δa = Joint normal displacement;

k_j = Joint permeability factor;

Δp = Pressure change;

L = Length assigned to contact between domains;

V = average of old and new volume;

ΔV = Mechanical volume change;

Q = Flow rate;

$\sum Q$ = Flow into node.

3. Methodology and Modeling

The geometry shown in Figure 1 is considered, in order to perform an investigation on the impact of groundwater table fluctuation on the stability of jointed rock slopes using DEM. The crest of the slope is at Elevation +10.0 m and the toe of the slope is at Elevation 0.0 m.

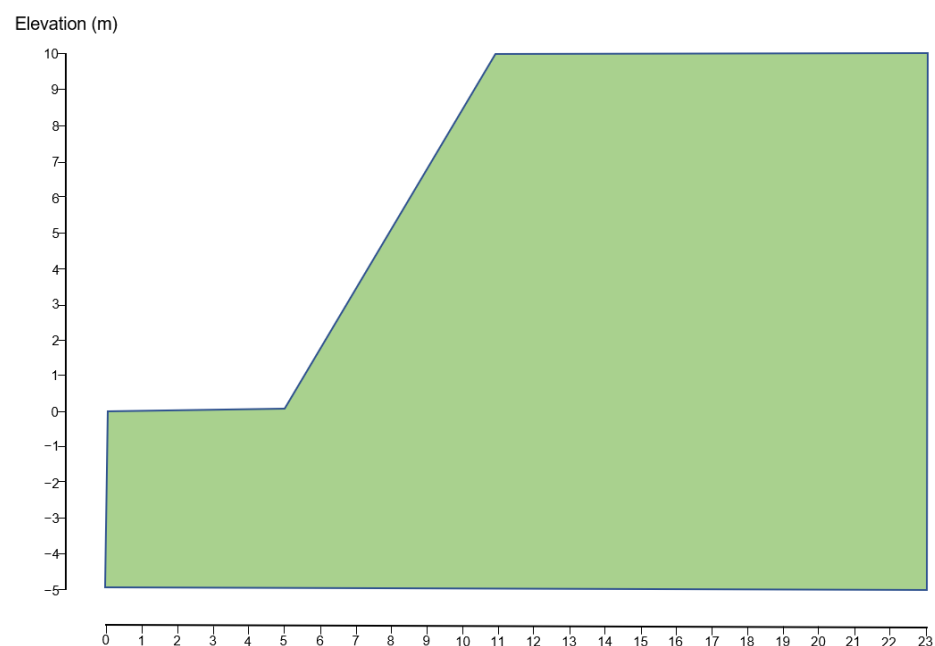


Figure 1. Geometry of model.

In this study, the groundwater level is raised to elevations of 1 m, 2 m, . . . , 10 m above the slope toe. The groundwater level at the right-hand side is raised to different elevations but the groundwater level on the left-hand side is maintained at the level of the slope toe and a steady-state flow analysis is performed in each case. The vertical boundaries of the model at the right-hand side (i.e., Elevations -5.0 to $+10.0$) and at the left-hand side of the slope base (i.e., Elevations -5.0 to 0.0) permit only vertical displacements. The bottom boundary is fixed in both vertical and horizontal directions and the top surface is unrestrained.

The properties of the rock blocks (intact rock) and rock joints considered in the modeling are presented in Tables 1 and 2, respectively. The density of groundwater is assumed to be 1000 kg/m^3 . Although the rock joint cohesion is not zero in reality, it is assumed that the discontinuities are cohesionless to be on the safe side in this study.

Table 1. Rock block properties.

Property	Unit	Value
Density	Kg/m^3	2500
Bulk Modulus	GPa	16.7
Shear Modulus	GPa	10.0
Internal Friction Angle	$^\circ$	60
Cohesion	MPa	100

Table 2. Rock joint properties.

Property	Unit	Value
Normal Stiffness	GPa/m	10
Shear Stiffness	GPa/m	10
Friction Angle	$^\circ$	26, 36, 46
Cohesion	MPa	0
Permeability Factor	$\text{MPa}^{-1} \text{ s}^{-1}$	1×10^8
Residual Hydraulic Aperture	m	2×10^{-4}
Aperture at Zero Normal Stress	m	5×10^{-4}

In sub-sections below, different number of joint sets, joint friction angles, joint spacings, and joint angles are considered. Table 3 summarizes all the cases considered in this parametric study.

Table 3. Summary of cases considered in parametric study.

Case No.	Varying Joint Parameter	Joint Sets	Joint Angle ($^\circ$)	Joint Spacing (m)	Joint Friction Angle ($^\circ$)	Groundwater Level Elevation (m)
1–20	Number of Joint Sets	J1, J2	J1: 15, J2: 78	J1: 2, J2: 1.5	26	1, 2, . . . , 10
		J1, J2, J3	J1: 0, J2: 15, J3: 78	J1: 3, J2: 2, J3: 1.5	26	1, 2, . . . , 10
21–50	Joint Friction Angle	J1, J2, J3	J1: 0, J2: 15, J3: 78	J1: 3, J2: 2, J3: 1.5	26	1, 2, . . . , 10
		J1, J2, J3	J1: 0, J2: 15, J3: 78	J1: 3, J2: 2, J3: 1.5	36	1, 2, . . . , 10
		J1, J2, J3	J1: 0, J2: 15, J3: 78	J1: 3, J2: 2, J3: 1.5	46	1, 2, . . . , 10
51–80	Joint Spacing	J1, J2, J3	J1: 0, J2: 15, J3: 78	J1: 6, J2: 4, J3: 2	26	1, 2, . . . , 10
		J1, J2, J3	J1: 0, J2: 15, J3: 78	J1: 1.5, J2: 1, J3: 0.75	26	1, 2, . . . , 10
		J1, J2, J3	J1: 0, J2: 15, J3: 78	J1: 1, J2: 0.5, J3: 0.38	26	1, 2, . . . , 10
81–110	Joint Angle	J1, J2, J3	J1: 0, J2: 15, J3: 57	J1: 3, J2: 2, J3: 1.5	37	1, 2, . . . , 10
		J1, J2, J3	J1: 0, J2: 15, J3: 65	J1: 3, J2: 2, J3: 1.5	37	1, 2, . . . , 10
		J1, J2, J3	J1: 0, J2: 15, J3: 81	J1: 3, J2: 2, J3: 1.5	37	1, 2, . . . , 10

3.1. Number of Joint Sets

Figure 2 shows two different number of joint sets including two (J1 and J2) and three joint sets (J1, J2, and J3), which are considered in this parametric study.

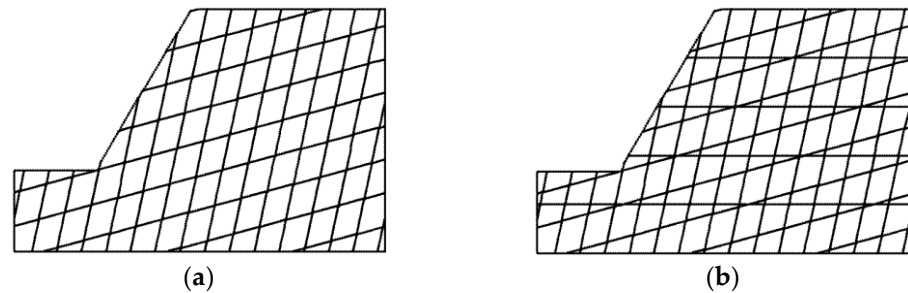


Figure 2. Configuration of models with different number of joint sets: (a) Two joint sets; (b) Three joint sets.

To investigate the impact of groundwater table fluctuation on stability of jointed rock slopes considering different number of joint sets, it is assumed that joint friction angle is 26° and different joint angles and spacings are considered, as presented in Table 3 as cases 1–20.

3.2. Joint Friction Angle

The friction angles considered in this study are 26° , 36° , 46° with three joint sets (J1, J2, and J3) and joint angles and spacings of J1: 0° , J2: 15° , J3: 78° and J1: 3 m, J2: 2 m, J3: 1.5 m, respectively, (cases 21–50 in Table 3).

3.3. Joint Spacing

As shown in Figure 3, three joint sets with spacings of (1) J1: 6.0 m, J2: 4.0 m, J3: 2.0 m, (2) J1: 1.5 m, J2: 1.0 m, J3: 0.75 m, and (3) J1: 1.0 m, J2: 0.5 m, J3: 0.38 m are considered. For these cases, joint angles of J1: 0° , J2: 15° , J3: 78° with a joint friction angle of 26° are considered, as presented in Table 3, cases 51–80.

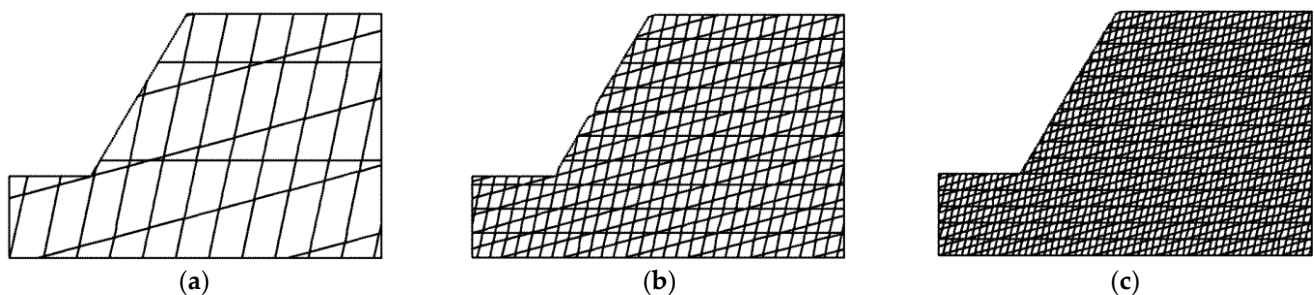


Figure 3. Configuration of models with different joint spacings: (a) J1: 6.0 m, J2: 4.0 m, J3: 2.0 m; (b) J1: 1.5 m, J2: 1.0 m, J3: 0.75 m; (c) J1: 1.0 m, J2: 0.5 m, J3: 0.38 m.

3.4. Joint Angle

Different sets of joint angles including (1) J1: 0° , J2: 15° , J3: 57° , (2) J1: 0° , J2: 15° , J3: 65° , and (3) J1: 0° , J2: 15° , J3: 81° are considered in this study, as shown in Figure 4. For these cases, a joint friction angle of 37° and joint spacings of J1: 3 m, J2: 2 m, J3: 1.5 m are considered as presented in Table 3 as cases 81–110.

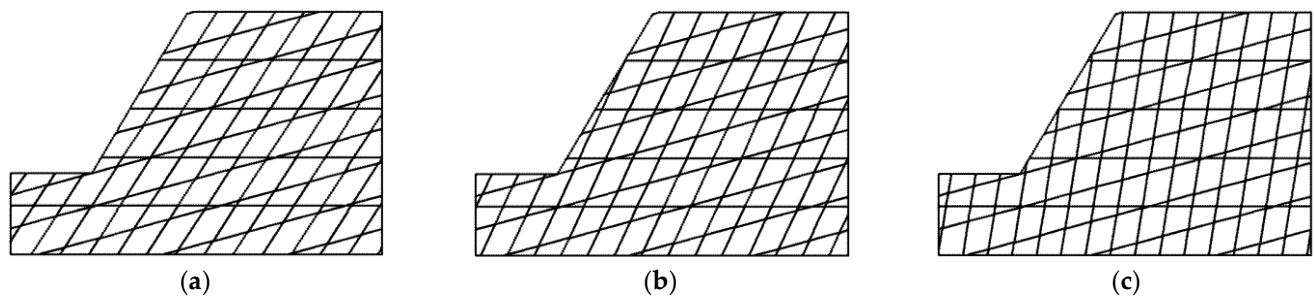


Figure 4. Configuration of models with different joint angles: (a) J1: 0°, J2: 15°, J3: 57°; (b) J1: 0°, J2: 15°, J3: 65°; (c) J1: 0°, J2: 15°, J3: 81°.

4. Results

The simulation results obtained from the UDEC modeling for different groundwater levels, number of joint sets, joint friction angles, joint spacings, and joint angles are presented below.

4.1. Effect of Number of Joint Sets

The factors of safety for different number of joint sets (cases 1–20) when the groundwater level elevation varies from 1 m to 10 m are presented in Figure 5. Increasing the groundwater level elevation decreases the factor of safety for all the cases, as expected. However, increasing the groundwater level elevation up to 3 m and 4 m does not affect the factor of safety for the cases with two and three joint sets, respectively.

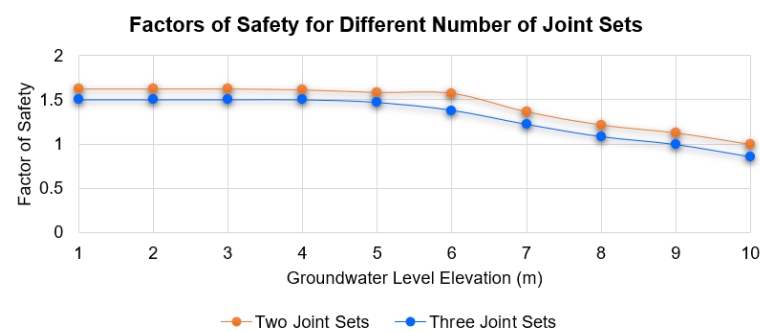


Figure 5. Factors of safety calculated for different number of joint sets.

4.2. Effect of Joint Friction Angles

Figure 6 shows the factors of safety for cases 21–50 (i.e., joint friction angles of 26°, 36°, and 46°) when the groundwater level elevation varies from 1 m to 10 m.

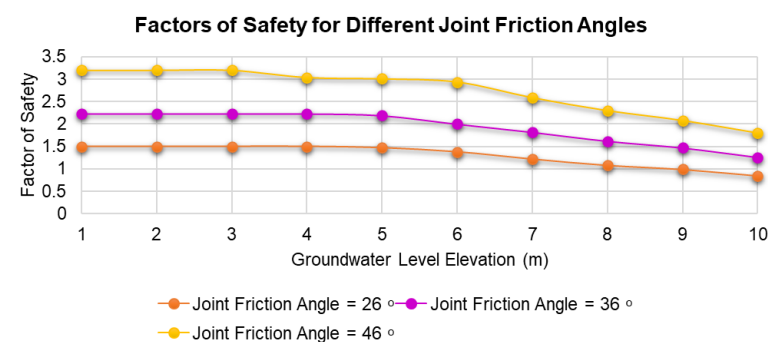


Figure 6. Factors of safety calculated for different joint friction angles.

It is evident that as the joint friction angle decreases, the calculated factor of safety decreases, and increasing the groundwater level elevation decreases the factor of safety for all the three cases. However, increasing the groundwater level elevation up to 4 m, 4 m, and 3 m does not influence the factor of safety for the cases with friction angles of 26° , 36° , and 46° , respectively. For the joint friction angles of 26° , increasing the groundwater level elevation to 10 m causes a landslide.

4.3. Effect of Joint Spacings

The factors of safety for three different sets of joint spacings, cases 51–80, when the groundwater level elevation varies from 1 m to 10 m are presented in Figure 7. The results show that increasing the groundwater level to an elevation higher than 5 m, 2 m, and 3 m decreases the factor of safety for the cases with joint spacings of (1) J1: 6.0 m, J2: 4.0 m, J3: 2.0 m, (2) J1: 1.5 m, J2: 1.0 m, J3: 0.75 m; (3) J1: 1.0 m, J2: 0.5 m, J3: 0.38 m, respectively. As the groundwater level elevation increases, the predicted failure surface of the initial stage of potential failure decreases and at high groundwater levels, a small-scale failure occurs at the toe of the slope which cause an initial stage of landslide occurs on the slope. For factors of safety less than 1.0, the lower factor of safety means that more robust stabilization measures are needed to prevent a landslide, although the predicted failure surface of the initial stage of failure is smaller.

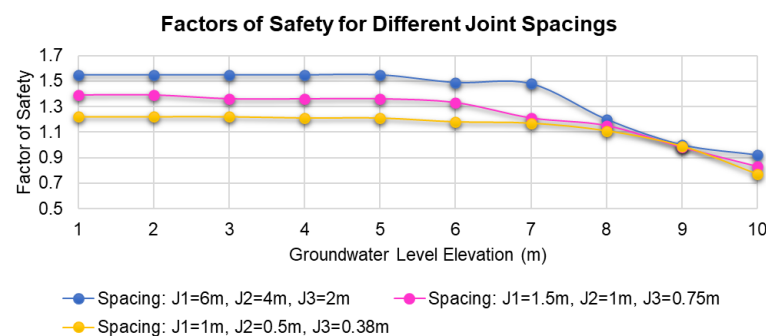


Figure 7. Factors of safety calculated for different joint spacings.

4.4. Effect of Joint Angles

Figure 8 shows the factors of safety for three different sets of joint angles (i.e., cases 81–110) when the groundwater level elevation varies from 1 m to 10 m. Moreover, Figures 9–11 show the velocity vectors and contours of total displacement indicating failure surfaces of the initial stage of potential failure. In these figures, the velocity vector shows the direction of rock block potential movement, and the greater velocity vectors and displacement contours indicate the initial stage of potential failure surface in each case. For the factors of safety equal to or higher than 1.0, the slope is stable, but for the factors of safety less than 1.0, the slope is unstable, and a landslide is expected to initiate with a failure surface, including the rock blocks with higher velocities and displacements.

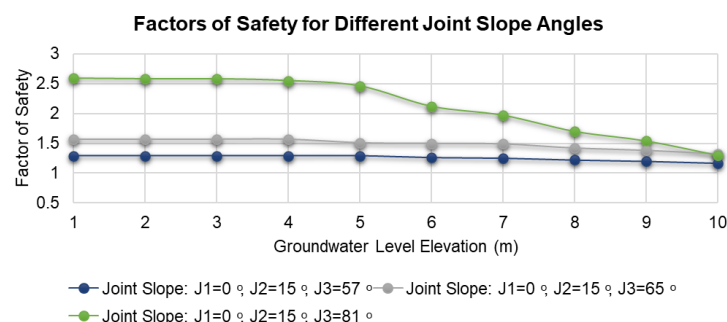
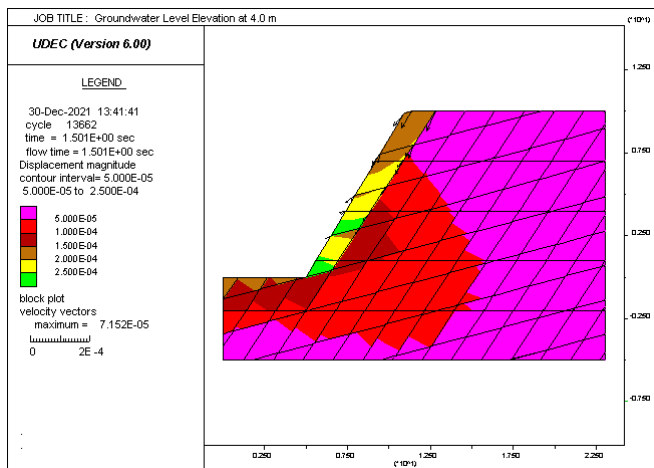
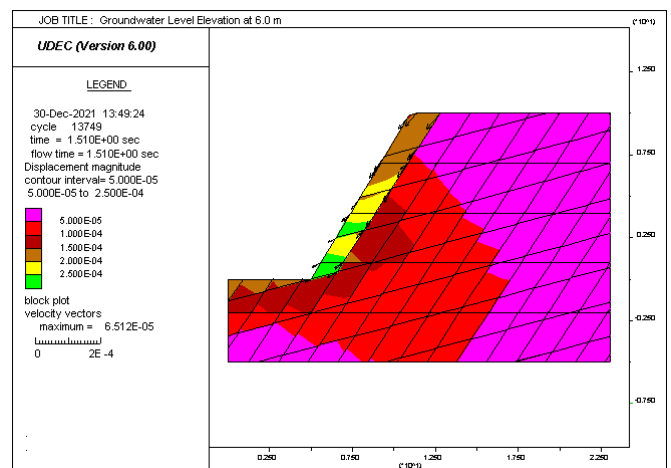


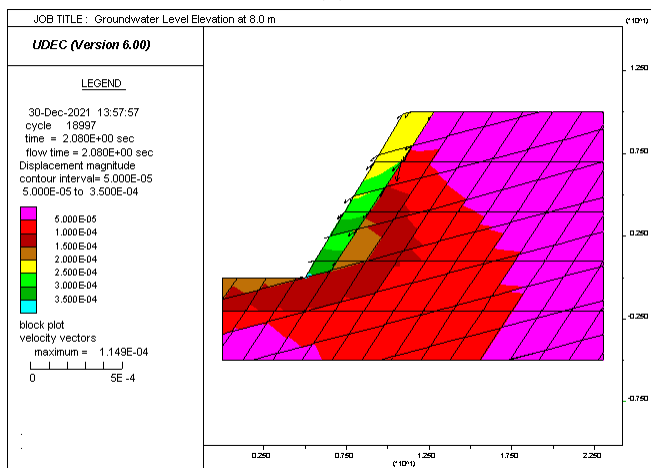
Figure 8. Factors of safety calculated for different joint angles.



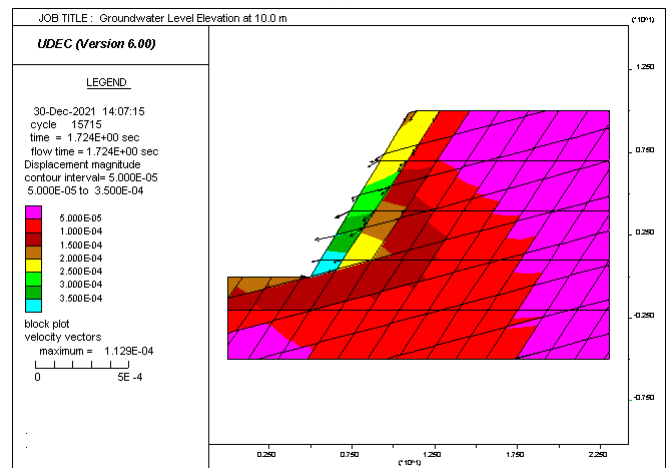
(a)



(b)

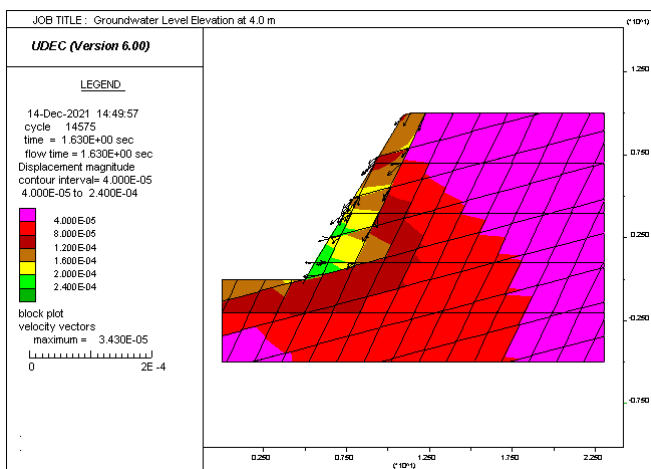


(c)

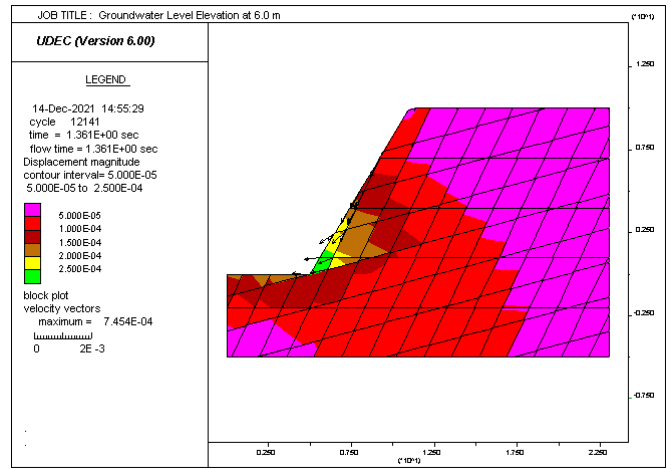


(d)

Figure 9. Slope with joint angles of J1: 0°, J2: 15°, J3: 57°: (a) Groundwater level elevation at 4 m; (b) Groundwater level elevation at 6 m; (c) Groundwater level elevation at 8 m; (d) Groundwater level elevation at 10 m.

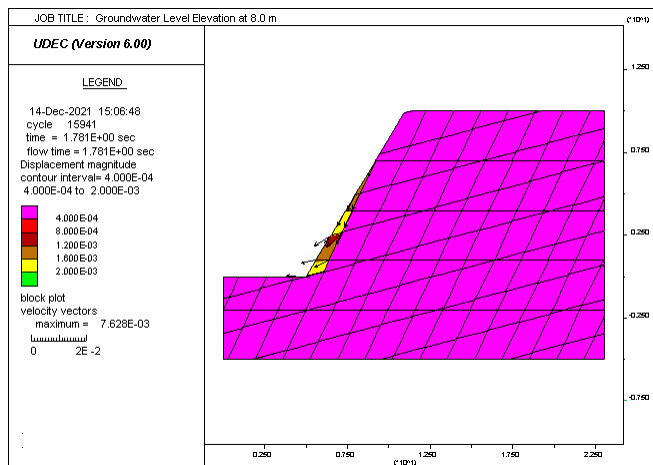


(a)

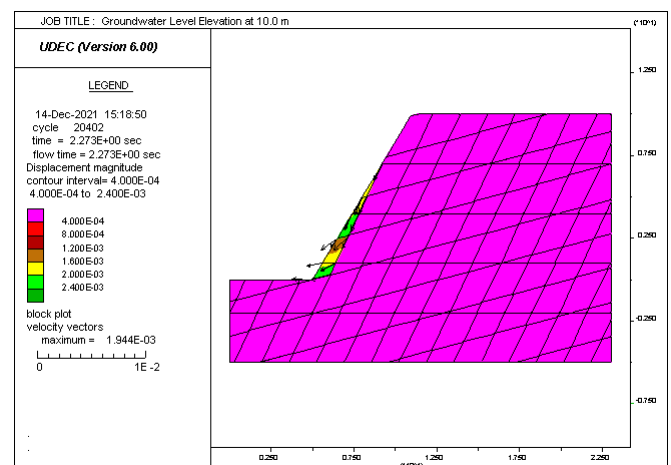


(b)

Figure 10. Cont.

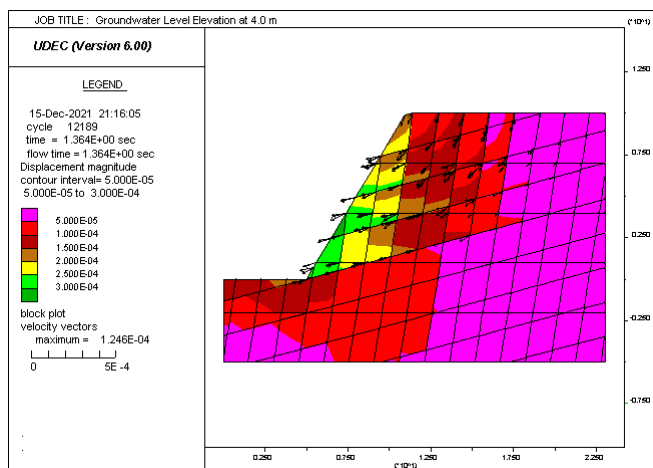


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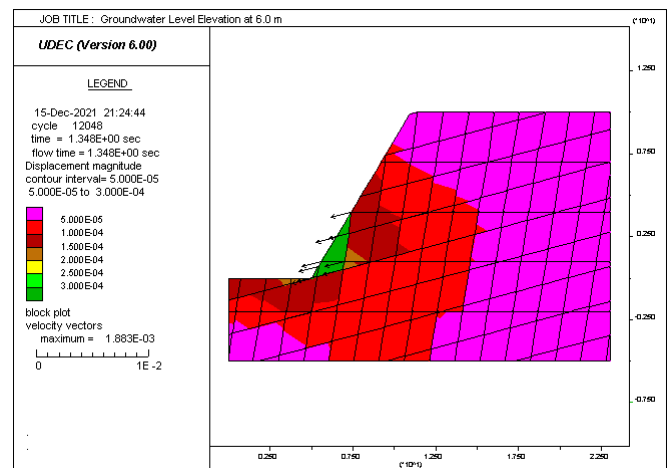


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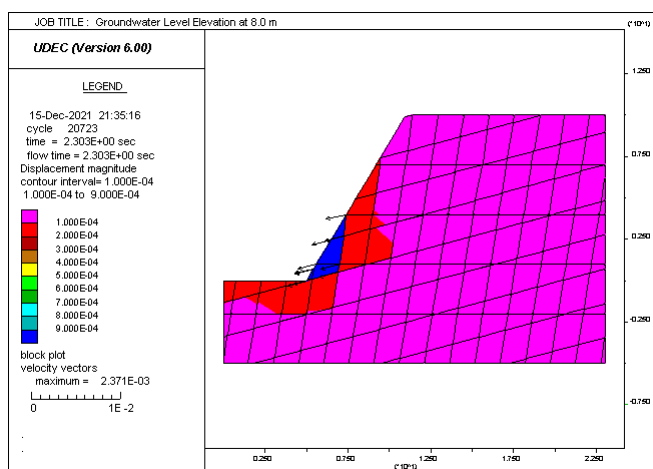
Figure 10. Slope with joint angles of J1: 0°, J2: 15°, J3: 65°: (a) Groundwater level elevation at 4 m; (b) Groundwater level elevation at 6 m; (c) Groundwater level elevation at 8 m; (d) Groundwater level elevation at 10 m.



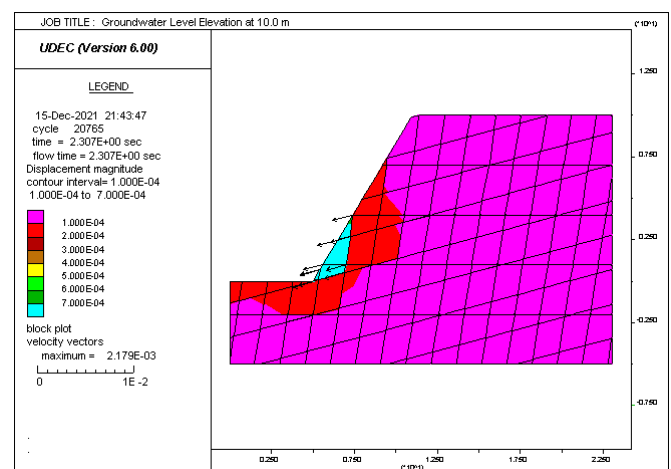
(a)



(b)



(c)



(d)

Figure 11. Slope with joint angles of J1: 0°, J2: 15°, J3: 81°: (a) Groundwater level elevation at 4 m; (b) Groundwater level elevation at 6 m; (c) Groundwater level elevation at 8 m; (d) Groundwater level elevation at 10 m.

It is evident that as the joint angle of the third joint set increases, increasing the groundwater level elevation has more impacts on the factor of safety.

5. Discussion

Tables 4–7 present the change in the factor of safety for different number of joint sets, joint friction angles, joint spacings, and joint angles, respectively, with respect to the case that the groundwater level elevation is located at 1.0 m. The results show that the variation of the groundwater level impacts the factor of safety so that increasing the groundwater level elevation decreases the factor of safety, as expected. In most cases, the slope is stable when the groundwater level is low, but when the groundwater table rises to higher levels, an obvious failure surface can be observed at the toe of the slope. The reason is that the failure of the slope occurs when the water pressure in the joints increases so that the effective normal stress in the joints decreases and water exerts hydrostatic pressure in rock joints and reduces the contact pressure and reduces the shear strength.

Table 4. Change in Factor of Safety (FS) For Different Number of Joint Sets with Respect to Case of Groundwater Level Elevation Located at 1.0 m.

Number of Joint Sets	Groundwater Level El. (m)	Change in FS (%)	Number of Joint Sets	Groundwater Level El. (m)	Change in FS (%)
2	2	0.00	3	2	0.00
2	3	0.00	3	3	0.00
2	4	−0.62	3	4	0.00
2	5	−2.47	3	5	−2.00
2	6	−3.09	3	6	−8.00
2	7	−16.05	3	7	−18.67
2	8	−25.31	3	8	−28.00
2	9	−30.86	3	9	−34.00
2	10	−38.89	3	10	−43.33

Table 5. Change in Factor of Safety (FS) For Different Joint Friction Angles with Respect to Case of Groundwater Level Elevation Located at 1.0 m.

Joint Friction Angle	Groundwater Level El. (m)	Change in FS (%)	Joint Friction Angle	Groundwater Level El. (m)	Change in FS (%)	Joint Friction Angle	Groundwater Level El. (m)	Change in FS (%)
26°	2	0.00	36°	2	0.00	46°	2	0.00
26°	3	0.00	36°	3	0.00	46°	3	0.00
26°	4	0.00	36°	4	0.00	46°	4	−5.00
26°	5	−2.00	36°	5	−1.79	46°	5	−5.94
26°	6	−8.00	36°	6	−10.31	46°	6	−8.13
26°	7	−18.67	36°	7	−18.39	46°	7	−19.06
26°	8	−28.00	36°	8	−27.35	46°	8	−28.13
26°	9	−34.00	36°	9	−34.08	46°	9	−35.00
26°	10	−43.33	36°	10	−43.50	46°	10	−43.75

Table 6. Change in Factor of Safety (FS) For Different Joint Spacings with Respect to Case of Groundwater Level Elevation Located at 1.0 m.

Joint Spacing (m)	Groundwater Level El. (m)	Change in FS (%)	Joint Spacing (m)	Groundwater Level El. (m)	Change in FS (%)	Joint Spacing (m)	Groundwater Level El. (m)	Change in FS (%)
J1 = 6 m, J2 = 4 m, J3 = 2 m	2	0.00	J1 = 1.5 m, J2 = 1 m, J3 = 0.75 m	2	0.00	J1 = 1 m, J2 = 0.5 m, J3 = 0.38 m	2	−0.82
	3	0.00		3	−2.16		3	−0.82
	4	0.00		4	−2.16		4	−0.82
	5	0.00		5	−2.16		5	−0.82
	6	−3.87		6	−4.32		6	−3.28
	7	−4.52		7	−12.95		7	−4.10
	8	−22.58		8	−17.27		8	−9.02
	9	−35.48		9	−29.50		9	−18.85
	10	−40.65		10	−40.29		10	−36.89

Table 7. Change in Factor of Safety (FS) For Different Joint Angles with Respect to Case of Groundwater Level Elevation Located at 1.0 m.

Joint Angle	Groundwater Level El. (m)	Change in FS (%)	Joint Angle	Groundwater Level El. (m)	Change in FS (%)	Joint Angle	Groundwater Level El. (m)	Change in FS (%)
J1 = 0°, J2 = 15°, J3 = 57°	2	0.00	J1 = 0°, J2 = 15°, J3 = 65°	2	0.00	J1 = 0°, J2 = 15°, J3 = 81°	2	−0.39
	3	0.00		3	0.00		3	−0.39
	4	0.00		4	0.00		4	−1.54
	5	0.00		5	−3.82		5	−5.02
	6	−2.33		6	−4.46		6	−18.15
	7	−3.10		7	−5.10		7	−23.94
	8	−5.43		8	−9.55		8	−34.36
	9	−6.98		9	−12.10		9	−40.54
	10	−9.30		10	−15.92		10	−49.81

Demonstrated in Table 6, there is 0% change in the factor of safety for the first set of joint spacing (i.e., J1 = 6 m, J2 = 4 m, J3 = 2 m) when the groundwater level elevation is below 6 m. The reason is that due to very large joint spacings in this case, the rock slope consists of very big (and heavy) blocks so that a high groundwater pressure is required to overcome the strength and to affect (i.e., decrease) the factor of safety.

The results obtained from the DEM modeling show that the maximum decrease in the factor of safety is similar for different joint friction angles when the groundwater level is high, so that the change in the factor of safety varies between −43.3% and −43.8% for joint friction angles of 26°, 36°, and 46°, respectively, when the groundwater level is at the ground surface.

Additionally, based on the results obtained from the numerical modeling, as the spacing of the joints decreases, the impact of increasing groundwater level elevation on the factor of safety decreases when the groundwater level is high. However, as the joint spacing increases, the groundwater level should get to a higher elevation to be able to impact the factor of safety, so that increasing the groundwater level elevation up to 5 m, 2 m, and 1 m does not affect the factor of safety for the cases with the joint spacings of (1) J1 = 6 m, J2 = 4 m, J3 = 2 m, (2) J1 = 1.5 m, J2 = 1 m, J3 = 0.75 m, and (3) J1 = 1 m, J2 = 0.5 m, J3 = 0.38 m, respectively.

Finally, it can be seen from the results that as the joint angles increase, increasing the groundwater level elevation decreases the factor of safety more, so that it causes −9.3%, −15.9% and −49.8% change in the factor of safety for the angles of the third joint set of 57°, 65°, and 81°, respectively, when the groundwater level is at the ground surface. In addition, the results show that groundwater table fluctuation has more impact on the factor of safety of the slopes with steeper joints, so that increasing the groundwater level elevation up to 5 m, 4 m, and 1 m does not affect the factor of safety for the cases with the joint angles of 57°, 65°, and 81°, respectively.

6. Conclusions

In this parametric study, different number of joint sets, joint friction angles, joint spacings, and joint angles are considered to obtain a better understanding of the impact of groundwater table fluctuation on the stability of jointed rock slopes. Based on the results obtained from the DEM modeling, the following conclusions are drawn:

- (1) The factor of safety can decrease significantly when the groundwater level increases (up to nearly 50% with a 9 m increase in groundwater level), which can cause a landslide.
- (2) The impact of groundwater table fluctuation on the factor of safety is similar for different joint friction angles when the groundwater level elevation is high.
- (3) As the spacing of the joints decreases, the impact of increasing groundwater level elevation on the factor of safety decreases. However, as the joint spacing increases, the groundwater level should rise to a higher elevation to be able to impact the factor of safety.

- (4) Groundwater table fluctuation has more impact on the factor of safety for the slopes with steeper joints.

Based on the above-mentioned conclusions and, for the sake of caution, it is recommended that geotechnical, civil, and mining engineers consider the highest possible groundwater level for slope stability analysis and the design of slope stabilization measures to prevent landslides in jointed rock slopes due to groundwater table fluctuation.

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