

Article Failure of Rock Slope with Heterogeneous Locked Patches: Insights from Numerical Modelling

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Abstract: Rock slope stability is commonly dominated by locked patches along a potential slip surface. How naturally heterogeneous locked patches of different properties affect the rock slope stability remains enigmatic. Here, we simulate a rock slope with two locked patches subjected to shear loading through a self-developed software, rock failure process analysis (RFPA). In the finite element method (FEM)-based code, the inherent heterogeneity of rock is quantified by the classic Weibull distribution, and the constitutive relationship of the meso-scale element is formulated by the statistical damage theory. The effects of mechanical and geometrical properties of the locked patches on the stability of the simulated rock slope are systematically studied. We find that the rock homogeneity modulates the failure mode of the rock slope. As the homogeneity degree is elevated, the failure of the locked patch transits from the locked patch itself to both the interfaces between the locked patched and the slide body and the bedrock, and then to the bedrock. The analysis of variance shows that length and strength of locked patch affect most shear strength and the peak shear displacement of the rock slope. Most of the rock slopes exhibit similar failure modes where the macroscopic cracks mainly concentrate on the interfaces between the locked patch and the bedrock and the slide body, respectively, and the acoustic events become intensive after one of the locked patches is damaged. The locked patches are failed sequentially, and the sequence is apparently affected by their relative positions. The numerically reproduced failure mode of the rock slope with locked patches of different geometrical and mechanical properties are consistent with the laboratory observations. We also propose a simple spring-slider model to elucidate the failure process of the rock slope with locked patches.

Keywords: rock slope; locked patch; shear strength; mechanical model

1. Introduction

Rock slopes usually contain geological discontinuities, such as flaws, joints, fissures, weak surfaces and even faults [1]. The rock slope is generally controlled by intact unfractured rock between discontinuities [2–6]. Intact unfractured rock provide shear resistance along the potential sliding surface and a complex interaction between existing natural discontinuities and brittle fracture propagation through intact rock is required to bring the slope to failure [7]. Experimental and numerical studies have been conducted to explore the failure process of intact rock, in which most are simplified as linear rock bridge ignoring thickness and emphasising the crack penetration [8–14]. The investigations on large rock slides indicate that the failure of actual rock slope is complicated. The Touzhai large-scale rock slide which occurred in Yunnan Province of China produced a deposit of 2400 m in length, 130 m in average width, and 10 m in thickness [15]. Strongly weathered basalt of 1 m thick was found in the source area and the intact basalt was inferred to control the rock slide. For the Xikou rock slide that occurred in Sichuan Province of China, it was postulated that the cemented fault breccia acted as a locking section to prevent the



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). deformation of the sliding body [16]. The field investigation revealed that the stability of Yinjiangyankou rock slide which took place in Guizhou of China is controlled by the intact rock patches located at the lower portion of the interlayer [17]. The intact hard structure along the possible sliding surfaces instead of linear rock bridge governs the rock slides. Some studies have focused on the locked rock slope [18–20] and summarised different types of locked rock slope in terms of engineering geology [21,22]. However, the failure process of intact rock patches remains to be revealed and interactions between different intact rock patches are still vague. We broadly define locked patch to represent the rock patches with higher strength along the potential sliding surface of a rock slope in this study (Figure 1) [23]. Only when all the locked patches fail, the rock mass starts to slide macroscopically. Therefore, failure of the locked patch possibly provides precursory information and thus early warning of rockslides [21].



Figure 1. Schematic of the rock slope with locked patches (Reprinted with permission from [23], 2021, Chinese Journal of Geophysics).

In our study, based on the self-developed, FEM-based code, RFPA (Rock Failure Process Analysis), we simulate the failure of two locked patches sandwiched by bedrock and slide body subjected to direct shear, analogous to the evolution of a rockslide. The effects of locked patch features on model stability and interactions between locked patches were investigated. The failure process and associated acoustic emission characteristics were analysed. Similar laboratory tests were employed to validate the numerical results. We also propose a simplified mechanical model to elucidate the failure process of the rock slope with locked patches. Our findings greatly advance our understanding on the failure of the rock slopes with locked patches.

2. Brief Description of RFPA and Numerical Model

We used the rock failure process analysis code (RFPA) to simulate the locked patch failure. The code has been widely adopted to simulate the mechanical behaviour of rock and rock mass under various loading conditions at both laboratory and field scales [24–30]. The elements of the rock are assumed to be linearly elastic, isotropic, and damage-free before loading. The mechanical properties of the elements are assigned statistically through a given Weibull distribution $\varphi(\alpha)$ [31] as follows:

$$\varphi(\alpha) = \frac{m}{\alpha_0} \cdot \left(\frac{\alpha}{\alpha_0}\right)^{m-1} \cdot e^{-\left(\frac{\alpha}{\alpha_0}\right)^m}$$
(1)

where α represents a given property of material; α_0 is a scaling parameter denoting the average value of the material property; *m* is a shape parameter representing material homogeneity.

The cumulative probability function $P(\alpha)$ is expressed as follows:

$$P(\alpha) = 1 - e^{-\left(\frac{\alpha}{\alpha_0}\right)^m}$$
⁽²⁾

The element damage obeys the one-dimensional linear elasticity law:

$$\sigma = E\varepsilon = E_0\varepsilon(1-D) \tag{3}$$

where σ , ε represent stress and elastic strain, respectively; *E* and *E*₀ are elastic modulus of damaged and undamaged material, respectively; *D* is the damage variable.

The constitutive relationship of an element under uniaxial tension is:

$$D = \begin{cases} 0 & \varepsilon \leq \varepsilon_{t0} \\ 1 - \frac{\sigma_{tr}}{E_0 \varepsilon} & \varepsilon_{t0} < \varepsilon \leq \varepsilon_{tu} \\ 1 & \varepsilon_{tu} < \varepsilon \end{cases}$$
(4)

where ε_{t0} is the elastic tensile strain limit; ε_{tu} is the ultimate tensile strain of the element. σ_{tr} is the residual uniaxial tensile strength. When the element is under uniaxial compression, the damage variable *D* is expressed as:

$$D = \begin{cases} 0 & \varepsilon \le \varepsilon_{c0} \\ 1 - \frac{\sigma_{cr}}{E_0 \varepsilon} & \varepsilon_{c0} < \varepsilon \end{cases}$$
(5)

where ε_{c0} is the elastic compression strain limit; σ_{cr} is the residual uniaxial compression strength.

Based on the stress and strain of the element and the chosen failure criterion (Mohr-Coulomb in this test), the damage state of element can be judged. The tensile criterion takes precedence over the compression and shear failure criterion in RFPA. Once the element is damaged, all the elastic energy stored in the element is released in the form of acoustic emission (AE). In the AE image, the element that reaches the tensile failure criterion is represented by a red circle while the shear failure element is represented by a white one and the circle diameter represents the relative size of AE energy.

Specifically, there is an empirical relationship between the mean element uniaxial compression strength and macroscopic uniaxial compression strength of samples using the following formula [32]:

$$\frac{\sigma_c}{\sigma_{c0}} = 0.2602 \ln m + 0.0233 (1.2 \le m \le 50)$$
(6)

where σ_{c0} is the mean element uniaxial compression strength. σ_c is the macroscopic uniaxial compression strength.

The locked patches control the locked rockslide where the weak fillings have limited effect. To understand the fracture process of the locked patches better, a series of simplified numerical simulations with omitted fillings was performed. As presented in Figure 2, the model was simplified to a plane model dimension of 10×5 m. After meshing, there were a total of $400 \times 200 = 80,000$ quadrilateral elements. The upper load was fixed, and the shear force was applied through the displacement-controlled mode. For the real rock slope, the geological settings are complex and the geometry and number of the locked patch are different. To simplify the calculation, the rock slope was simplified in two intact locked patches sandwiched by a bedrock and a slide body. The mechanical parameters of the left locked patch are constant and the right locked patch has identical magnitude of the elastic modulus but with different strength, length, height, depth, and homogeneity. The locked patches share the same node elements with bedrock and slide body on the interface. It should be noted that the failure of the interface is mainly affected by the small deformation failure of the element and the mechanical behaviour of the locked patch. In the meantime, we focus on the effect of the mechanical parameters of the locked patch on the

model stability while do not study large displacement friction behaviour of the interface. Therefore, based on the continuum mechanics, the mechanical behaviour of the interface is equivalent to the deformation and failure behaviour of the surface elements. Table 1 lists the mechanical and physical properties of the model. The normal stress was prescribed at 0.5 MPa, according to the fact that the maximum effective normal stress ranges from 0.1 to 2.0 MPa in many rock engineering problems [33].



Figure 2. Illustration of the numerical model.

Parameters	Rock Mass	Left Locked Patch	Right Locked Patch
Elastic modulus (GPa)	50	40	40
Poisson's ratio	0.25	0.25	0.25
Ratio of compressive and tensile strength	10	10	10
Angle of internal friction (°)	30	30	30
Mean element uniaxial compressive strength * (MPa)	300	200	100, 150, 200, 250, 300
Length (m)	10	0.5	0.1, 0.25, 0.5, 1.0, 1.5
Spacing (m)	-	0.5, 2, 4, 5, 6	0.5, 2, 4, 5, 6
Depth (m)	5	0.5	0.5, 0.6, 0.7, 0.8, 0.9, 1.0
Height (m)	-	0.5	0.5, 0.6, 0.7, 0.8, 0.9, 1.0
Homogeneity index, <i>m</i>	3	3	1, 2, 3, 4, 5

Table 1. Input parameters for numerical modelling.

* The relationship between mean uniaxial compressive strength of element and macroscopic uniaxial compression strength of sample is shown in Equation (6).

3. Numerical Results

3.1. Strength Effect

Figure 3a shows the failure process of the simulated rock slope with locked patches of the same uniaxial compressive strength. Shear stress concentrates obviously in the locked patches whereas the shear stress of the bedrock and the slide body are relatively low. As the shear stress grows, the left locked patch first begins to fail. The cracks initially occur at the top right corner and the bottom left corner of the locked patches. Then two parallel crack bands gradually expand along the interface between the locked patch and the bedrock and slide body symmetrically whereas little damage has been caused within the locked patch, bedrock, and slide body. The numerically reproduced stress localisation zone is consistent with the experimental results where the locked patch failed progressively with identifiable strain localisation zones [20]. The two locked patches exhibit similar failure modes and only when both locked patches are failed, the model becomes completely unstable. Therefore, the locked patch with higher shear strength and peak shear displacement controls the model stability. Namely, the shear strength and peak shear displacement of the model can be considered as the larger values of the two locked patches. The models with different strength locked patches have the similar failure pattern. Most cracks are distributed on the interfaces of locked patches while few cracks are found in the locked patch, bedrock, and slide body.





(a)

Figure 3. Cont.





Figure 3b shows that the corresponding AE distribution is consistent with the shear stress distribution where the failure is mainly concentrated on the interfaces between the locked patch and bedrock and slide body. It shows that a large number of AE initially appears in the left locked patch, and then in the right locked patch, suggesting that the stress is being transferred from the left locked patch to the right one. For the slide body under shearing, the AE distribution demonstrates that the rockslide is mainly caused by tensile failure of the locked patch. In other words, the tensile failure of the elements leads to the macroscopic shear failure of the model.

Figure 4 shows the shear stress–shear displacement–acoustic emission curves of the model with locked patches of different strength. In the early stage, shear stress–displacement curves of two locked patch basically overlap and little damage has been caused. The increasing displacement leads to the damage of locked patch and visible increase of AE counts and energy. AE can be divided into two parts, i.e., that released in the post-peak of the first broken locked patch and the failure of the second broken locked patch. AE distribution in Figure 3b indicates that little energy is released after the failure of the locked patch. Therefore, the second broken locked patch is responsible for the AE after the first peak stress.



Figure 4. Effect of strength on the relationships between shear displacement and shear stress, AE counts, and AE accumulative energy.

Figure 5 summarises the relationship between the strength of the locked patch versus peak shear displacement and shear strength. For convenience, the locked patch, shear strength, and peak shear displacement are abbreviated as LP, SS, and PSD, respectively, in the figure. It should be noted that the break of one locked patch does not cause the immediate failure of the rock slope. The maximum peak shear displacement of the last broken locked patch can be up to twice as much as that of the first broken locked patch

(Figure 4). On the other hand, it shows that both the shear strength and peak shear displacement of the right locked patch increase as its strength becomes higher. The variation of the strength of the right locked patch poses little effect on the displacement of the left locked patch where the peak shear displacement of the left locked patch remains constant with small fluctuations. However, the shear strength of the left locked patch decreases with the increasing strength of the right locked patch (Figure 5). As the mechanical properties of the left locked patch leads to the corresponding change of the left one. It appears that the increasing strength of the right locked patch leads to the stress redistribution which finally affects the strength of the left locked patch. Namely, there is an interaction between two locked patches.



Figure 5. Relationships between uniaxial compressive strength of right locked patch and shear strength and peak shear displacement of two locked patches. LP denotes locked patch, and SS and PSD represent shear strength and peak shear displacement, respectively.

3.2. Length Effect

The failure pattern of the rock slope with different length of locked patches resembles the numerical models with locked patches of different strength where cracks are mainly distributed along the interface of the locked patch. It also yields similar shear stress–shear displacement–acoustic emission relationships. Figure 6 summarises the variation of AE, shear strength, and peak shear displacement with length of right locked patch. With the increased length of right locked patch, accumulated AE counts and energy of two locked patches increase while the peak shear displacement and strength of two locked patches initially increase and then decrease. The effect of right locked patch length on the left one can be divided into two stages. When the length of right locked patch increases from 0.1 to 0.25 m, the strength of the left locked patch increases by 61%. When the length of right locked patch increases from 0.25 to 1.5 m, the difference between the maximum and minimum is only 2.8 MPa. The peak shear displacement of the left locked patch presents the similar trend.



Figure 6. (a) Accumulated AE counts and energy variation with respect to length of right locked patch. (b) Shear strength and peak shear displacement variation with respect to length of right locked patch. LP denotes locked patch, and SS and PSD represent shear strength and peak shear displacement, respectively.

3.3. Spacing Effect

Figure 7a shows that the peak shear displacement and shear strength of the right locked patch first decrease followed by an increase with the increasing spacing. The shear strength and peak shear displacement of left locked patch increase with the spacing. The different trend can be attributed to the unchanged position of the left locked patch and changing position of the right one. The larger spacing denotes the increased distance from the location of force loading for right locked patch. It suggests that rock slope stability can be improved when the locked patch is located at the toe of the slope. The differences of the peak shear displacement and shear strength of two locked patches are summarised in Figure 7b. As the spacing grows from 0.5 to 6 m, the difference of peak shear displacement decreases from 4.4 to 0.2 mm, while the difference of shear strength decreases from 17.8 to 2.2 MPa. It is conceivable that when the spacing is sufficiently long, two locked patches will have the same shear strength and peak shear displacement. That is to say the effect of spacing only works within a certain range.



Figure 7. (a) Relationships among locked patch spacing, shear strength and peak shear displacement; (b) effect of locked patch spacing on the differences of the peak shear displacement and shear strength between two locked patches. LP denotes locked patch, and SS and PSD represent shear strength and peak shear displacement, respectively.

3.4. Depth Effect

The locked patch depth mainly affects the failure mode. Figure 8a shows that the increasing depth of right locked patch presents little effect on the failure model of the left locked patch while the failure of the right locked patch extends gradually from the interface to the bedrock forming a U-shaped pit. The pit depth is unproportioned to the locked patch depth where the pit depth increases preceding a decreasing stage. The model with a 0.8 m deep right locked patch generates the deepest pit. The effect of right locked patch gatch depth on the shear strength and peak shear displacement of the two locked patches are summarised in Figure 9a. The shear strength and peak shear displacement of the left locked patch fluctuate slightly within a small range and decrease first while followed by an increased stage with the depth. The right locked patch presents same variation trend with the left one. The model with a 0.8 m deep right locked patch patch presents the smallest shear strength, smallest peak shear displacement, and the deepest pit. The pit depth is close to the mechanical parameters of the locked patches.







Figure 8. Failure patterns of models (**a**) with different depth of right locked patches; (**b**) with different homogeneity of right locked patches.



Figure 9. Cont.



Figure 9. Relationships between (**a**) the depth of right locked patch, (**b**) the height of right locked patch, (**c**) the homogeneity of right locked patch vs. shear strength and peak displacement of two locked patches. LP denotes locked patch, and SS and PSD represent shear strength and peak shear displacement, respectively.

3.5. Height Effect

The failure pattern of the model with different locked patch heights is similar to that with different strengths where macro cracks concentrate on the interface of locked patches. Compared with the locked patch embedded in the bedrock, the locked patch embedded in the slide body hardly affects the failure pattern. Figure 9b shows that both the shear strength and peak shear displacement of two locked patches initially increase and decrease later with the locked patch height and most maximise at the height of 0.7 m. The height of right locked patch has limited effect on the left one where the differences between the maximum and minimum of the shear strength and peak shear displacement are only 2.1 MPa and 0.8 mm, respectively.

3.6. Homogeneity Effect

The change in homogeneity of right locked patch leads to three different failure patterns of the right locked patch. For the model with a lower homogeneity degree, damage occurs within the right locked patch (Figure 8b). The increased homogeneity leads to the failure gathering on the interfaces of the right locked patch. When the homogeneity index increases to 5, pits are formed in the bedrock. However, the homogeneity variation has little effect on the failure pattern of the left locked patch where its failure is still concentrated on the interfaces of the locked patch. The shear strength and peak shear displacement of the locked patch grow with the homogeneity. The left locked patch exhibits an opposite change where the shear strength and peak shear displacement decrease with a higher homogeneity degree. It indicates that the increased homogeneity of the right locked patch weakens the effect of the left locked patch on the model stability.

3.7. ANOVA Analysis

To determine the weighting contribution of each input (e.g., strength, length, spacing, depth, height, and homogeneity in this study) to output (e.g., shear strength and peak shear displacement), analysis of variance (ANOVA) was employed to quantify the effects. The total sum of squares, *SST*, which shows the total variability of response, is calculated as follows:

$$SST = \sum_{i=1}^{i=r} \sum_{j=1}^{j=m} (y_{ij} - \bar{y})^2$$
(7)

where y_{ij} denotes the response of *ij*th experiment; \overline{y} denotes the mean response of the total experiments [34]. The total sum of squares is composed of two sources of the sum of squares due to each factor and the error sum of squares *SSE*, which can be given by:

$$SSE = \sum_{i=1}^{i=r} \sum_{j=1}^{j=m} (y_{ij} - \overline{y_{i.}})^2$$
(8)

$$SSF = SST - SSE = m \sum_{i=1}^{i=r} (\overline{y_{i.}} - \overline{y})^2$$
(9)

where $\overline{y_{i}}$ denotes the mean response of the levels of the factor *i*.

The total mean square, error mean square, and each factor mean square can be calculated by dividing the corresponding degree of freedom (DOF). DOF can be given by:

$$dft = r \times m - 1 \tag{10}$$

$$dfe = r \times (m-1) \tag{11}$$

$$dff = r - 1 \tag{12}$$

$$F = \frac{MSSF}{MSSE} = \frac{SSF/dff}{SSE/dfe}$$
(13)

The *F* value of each factor can be obtained by the ratio of mean square of factor to the mean square of error:

The *F*-test is undertaken to evaluate the significance of each parameter. The calculated *F* values are compared with *F*-distribution values with specific confidence levels. If the *F* value is greater than the *F*-distribution value, it means that the factor has a significant effect on the response with that specified level of confidence. Namely, a larger value of *F* value means the effect is more pronounced. Therefore, the weighting contributions of different parameters are based on the *F* value.

The results of ANOVA are calculated and presented in Tables 2 and 3. The effect of different parameters on the shear strength and peak shear displacement can be divided into three groups. The length of locked patch has the greatest effect on the shear strength and peak shear displacement where the weightings are more than 46%, and 86%. In the case of the strength and spacing of the locked patch, they have the similar effect where the average weightings of the shear strength and peak shear displacement are 17.6% and 4.1%, respectively. In the case of the locked patch depth, height, and homogeneity, the results indicate that they have limited effect on the rock slope. The sum of the three weights in peak shear displacement is only 5.8%. Compared with the other parameters, the influence of these three parameters on the peak shear displacement can be ignored. The average weight of these three parameters in shear strength is only 6.2%. Therefore, the attention should be focused on the strength, length, and spacing for the locked rock slope with two locked patches.

Table 2. Summary of ANOVA for shear strength.

Parameters	Sum of Squares	DOF	Mean Square	F Value	Weighting Contribution
Strength (MPa)	68.64	4	17.16	1.63	17.17
Length (m)	184.91	4	46.23	4.38	46.26
Spacing (m)	72.03	4	18.01	1.71	18.02
Depth (m)	27.52	5	5.50	0.52	5.51
Height (m)	32.92	5	6.58	0.62	6.59
Homogeneity, <i>m</i>	32.27	4	8.07	0.61	6.46

Parameters	Sum of Squares	DOF	Mean Square	F Value	Weighting Contribution
Strength (MPa)	10.05	4	2.51	1.32	4.93
Length (m)	175.28	4	43.82	22.98	86.02
Spacing (m)	6.72	4	1.68	0.88	3.30
Depth (m)	1.99	5	0.40	0.26	0.97
Height (m)	8.64	5	1.73	1.13	4.24
Homogeneity, <i>m</i>	1.08	4	0.27	0.14	0.53

Table 3. Summary of ANOVA for peak shear displacement.

4. Comparisons with Experimental Observations

4.1. Comparison of Failure Pattern

The failure patterns of similar experimental tests with two locked patches are shown in Figure 10 [17]. It exhibits similar failure patterns where pits were formed within locked patches which is consistent with numerical models with locked patches of different depth in Section 3.4. The same as with the simulation results, the experiments also show that the length of locked patch and spacing posed little effect on failure pattern. Except for the locked patch embedded in bedrock, little damage occurs within the locked patch and bedrock. The locked patch, slide body and bedrock remain relatively intact after the slope fails.





(c)

Figure 10. Rockslides reproduced in the physical experiment. (**a**) Same-length locked patches with a large spacing, (**b**) short upper locked patch with a large spacing, (**c**) same-length locked patches with a small spacing (Reprinted with permission from [17], 2021, Springer Nature).

4.2. Comparison of Mechanical Parameters

The experiments on the sample with two saw-tooth asperities are used to compare with the numerical results [35]. The effects of length on the shear strength are summarised in Figure 11a. As the length of locked patch/saw-tooth asperity increases, the shear strength of numerical model increases first and is followed by a decreased stage while the strength of sample increases evidently. A different trend occurs on the peak shear displacement as well. Figure 11b shows that the peak shear displacement of the model presents an increasing trend, while that of the sample decreases first followed by an increased stage with the length of locked patch/saw-tooth asperity. The shear strength of the sample has the similar variation trend with the peak shear displacement of the model. The peak shear displacement of the sample has the opposite variation trend with the sensitivities on the model. It suggests that different locking structural forms have different sensitivities on the shear strength and peak shear displacement.



Figure 11. Cont.



Figure 11. Comparisons between numerical results and experimental results. (**a**) Total length vs. shear strength, (**b**) total length vs. peak shear displacement, (**c**) spacing vs. shear strength, (**d**) spacing vs. peak shear displacement, (**e**) total height vs. shear strength, (**f**) total height vs. peak shear displacement.

The spacing of locked patch and saw-tooth asperity present the same trend on the shear strength where the increasing spacing leads to a decreasing shear strength (Figure 11c). Specifically, they can be divided into two stages. In the case of the sample with saw-tooth asperity, a dramatic decrease occurs once the spacing exceeds 40 mm. Similar sharp decline happens when spacing of locked patch surpasses 0.5 m. The peak shear displacement of the samples and model decrease with the increasing spacing first and increase in the end (Figure 11d). The same trend of numerical and experimental results suggests that the effect of spacing on the rock slope stability is independent with the locking structural form and smaller spacing is conducive to the slope stability.

As the total height increased, the shear strength and peak shear displacement of the sample and model both present an increasing trend first while followed by a decreasing stage (Figure 11e,f). The peak shear displacement and shear strength of the model reach the maximum at the same height. A slight difference exists on the height corresponding to the maximum peak shear displacement and shear strength of the sample. It can be roughly deemed that there is an optimal height for the slope stability in which the shear strength and peak shear displacement are larger than the others. Moreover, the same trend of simulation and experiment suggests that the effect of height on the slope stability is independent with the locking structural form as well.

5. Mechanical Model of Locked Patch

The above analysis shows that the failure patterns of the locked patches differ, which makes it difficult to represent the mechanical behaviour by a simple model. However, it should be noted that most of the numerical and experimental results yield similar failure patterns where the crack expands along the interface between the locked patch and rock slope, whereas little damage occurs within the bedrock, the slide body, and the locked patch; thus, they can be simplified as rigid bodies. Figure 12 illustrates the simplified model to illuminate the failure process of the locked patch. Since the crack propagation on the upper and lower interfaces of the locked patch is almost synchronous and symmetric, only the interface between the bedrock and the locked patch is analysed. For a locked patch confined by a normal stress subjected to shear, its shear resistance (R_s) is:

$$R_s = R_n tan \varnothing + cl_c \tag{14}$$



where R_n denotes the normal stress, \emptyset is the friction angle, *c* is the cohesion per unit length, and l_c is the contact length between the locked patch and the bedrock.

Figure 12. Schematic of the contact states: (**a**) stationary state, (**b**) sliding state, (**c**) separated state, (**d**) simplified model with two locked patches, and (**e**) fitting curves of the model with two identical locked patches.

The locked patch is represented by a slider and a spring in series (Figure 12). There are three possible types of contacts between the bedrock and the slider. When the shear loading is less than the shear resistance of the slider, the slider remains stationary (Figure 12a). When the shear loading exceeds R_s , the slider begins to slide along the interface (Figure 12b). The effective contact area between the slider and bedrock decreases gradually. When l_c decreases to 0, the slider is separated from the bedrock and the slider completely loses its resistance (Figure 12c).

For the model with two locked patches, the shear displacement of the slide body and the locked patches are identical. The two locked patches are parallel connected. The stiffness of the first and second locked patch are k_1 and k_2 , respectively. The force of the first and second spring F_{s1} and F_{s2} can be calculated by:

$$u = u_1 = u_2 \tag{15}$$

$$F_{s1} = ku_{11}$$
 (16)

$$F_{s2} = ku_{21}$$
 (17)

where u is the shear displacement of the slide body; u_1 and u_2 are shear displacements of first and second locked patch, respectively. u_{11} and u_{21} are displacements of the first and second spring, respectively. When the shear displacement is small, the force of the spring is also small. Therefore, the slider remains stationary. In this stage, the locked patch can be simplified into a spring. Later, the increased displacement increases the force of the spring as well. When the force of the spring is larger than the shear resistance of the slider, the slider begins to slide. The sliding of the slider decreases the contact length. Correspondingly, spring elongation decreases and the force of spring decreases. The force of spring F_s and slider in this stage is calculated by:

$$F_s = k(u_{spmax} - \Delta u_{sp}) \tag{18}$$

$$R_s = R_n tan \varnothing + c(l_c - \Delta u_{sl}) \tag{19}$$

where u_{spmax} is the maximum elongation displacement of the spring; Δu_{sp} and Δu_{sl} are the variations of the shear displacement of spring and slider, respectively. The relationship between shear displacement variations of the slide body and the locked patch is:

$$\Delta u = \Delta u_1 = \Delta u_2 = \Delta u_{sl} - \Delta u_{sp} \tag{20}$$

where Δu , Δu_1 , and Δu_2 are the shear displacement increments of the slide body, the first locked patch, and the second locked patch, respectively. As the shear displacement grows, the locked patch loses its shear resistance completely when the slider is separated from the bedrock.

Since the two locked patches are parallel connected, the failure of one locked patch does not lead to the failure of the model. Therefore, based on the equations above, the analytical estimations of the model with two same locked patches are given in Figure 12e. The analytical results agree well with the numerical results. For the right locked patch, the estimated cohesion per unit length is 38 MPa/m, and the shear strength is 2 MPa. For the left locked patch, the estimated cohesion per unit length is 21 MPa/m, and the friction strength is 2.3 MPa. This suggests that the shear strength is similar for different locked patches, while the difference is mainly on the cohesion. Moreover, the higher values of the estimated cohesion per unit length suggest that the length of the locked patch is crucial on the shear strength of the locked rock slope which agrees well with the ANOVA analysis.

6. Conclusions

We modelled a simplified rock slope sandwiching two locked patches through RFPA to investigate mechanical and geometrical properties of locked patch on slope stability. The failure process and AE evolution over the sequential damage of the locked patches were analysed. The main conclusions are as follows:

(1) Macro cracks are mainly concentrated on the interfaces between the locked patch and bedrock and slide body, respectively, whereas little damage occurs within the bedrock, slide body, and locked patch. AE distributions indicate that localised tensile failure leads to the macroscopic shear band along the interfaces.

(2) The shear strength and peak shear displacement of the model ascend with the increasing strength and homogeneity. As the lock patch is longer, the peak shear displacement grows whereas the shear strength first increases and then decreases. With an increasingly larger spacing, both the peak shear displacement and shear strength decrease first and then increase. On the contrary, the peak shear displacement and strength of the slope initially increase, followed by a decrease when the locked patch becomes higher. The depth of locked patch has little effect on the peak shear displacement and shear strength. The ANOVA analysis shows that the length of locked patch dictates the peak shear displacement and the shear strength. The spacing and strength of the locked patch pose almost

the same effect on the slope shear strength and peak shear displacement. The height, depth, and homogeneity of the locked patch have negligible influence on the shear strength and peak shear displacement.

(3) The numerical simulations agree well with the experimentally observed failure modes reported in the literature. The numerical model with locked patch and the sample with saw-tooth asperity present the same trend on the shear strength and peak shear displacement with spacing and height, while they present a different trend with the increased length.

(4) Based on the failure mode, the locked patch was simplified into the model of a spring and a slider connected in series. The simplified model can elucidate the failure process of the rock slope with locked patches.

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