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# Effect of buttress on reduction of rock slope sliding along geological boundary

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ABSTRACT

In open-cut limestone mines in Japan, huge rock slopes with a geological boundary between limestone and bedrock have been formed by mining activities. In addition, latent sliding plane near the toe of the slopes may be formed through the development of damaged zones with an increase in size of the rock slope. It has been reported that inelastic time-dependent sliding deformation of rock slopes along both the geological boundary and the latent sliding plane can occur. In this case, one of the countermeasures to suppress sliding deformation is an application of rock buttress to the slope surface where the sliding is taking place. However, the effect of rock buttress on reduction of the rock slope sliding has not yet been clarified. In this paper, the effect of rock buttress on reduction of the rock slope sliding is discussed based on a 2-dimensional finite element analysis using a non-linear visco-elastic model. The results indicate that (i) the degree of deterioration of sliding plane at the time of the application of rock buttress significantly affects the expected life of rock slope, (ii) there is an optimum height for rock buttress,, (iii) larger Young's modulus of rock buttress results in a longer expected life of rock slope, and (iv) the balance of increase and decrease of normal and shear stresses on the sliding plane by buttress is important and the obtained results can be changed by the difference of friction angle and the geometry of the sliding plane.

## 1. INTRODUCTION

In open-cut limestone mines in Japan, huge rock slopes have been formed by mining activities (Obara et al., 2000). In Japan, limestone deposit is often found on inclined bedrock and a part of the limestone deposit is left on the bedrock, such as schalstein to prevent the bedrock from weathering (Nakamura et al., 2003). Thus, the rock slopes include a geological boundary between limestone and bedrock. In addition, with increases in size of the rock slope, the stress state near the toe of slope can be severe and a damaged zone can develop. Therefore, it is necessary to pay attention to the deformation behaviour at the geological boundary and the toe of slope for the estimation of slope stability. Moreover, it is important to consider effective countermeasures in case dangerous signs such as sliding deformation at these parts are observed. One of the countermeasures to suppress the sliding deformation is application of rock buttress to the slope surface where the sliding is taking place. However, the effect of rock buttress on reduction of the sliding has not yet been clarified.

In this paper, the effect of rock buttress on reduction of inelastic time-dependent rock slope sliding, for example, how the height and stiffness of rock buttress affects slope deformation is discussed based on self-developed 2-dimensional (2-D) finite element code using a non-linear visco-elastic model.

## 2. MODELLING SLIDING DEFORMATION OF ROCK SLOPE

The aforementioned inelastic time-dependent sliding deformation of rock slope was modelled first to investigate the effect of rock buttress on the reduction of the sliding. Figure 1 shows the 2-D model of rock slope with geological boundary (blue line) and latent sliding plane (red line). Hereafter the term "sliding plane" is used to indicate both geological boundary and latent sliding plane. It was assumed that the rock slope was already formed by partially excavating the left side of a mountain. The height and angle of slope were set at 270 m and 45°, respectively. The geological boundary was set parallel to the slope surface and latent sliding plane from the slope surface, with an angle of 18° from the horizon, and intersected with geological boundary near the toe of slope. The intact rock mass was represented by 6-node and 8-node solid elements and assumed to be isotropic linear elastic body, while the

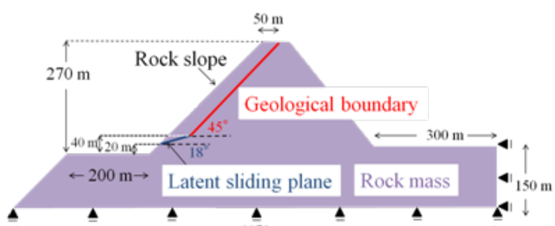


Figure 1: Schematic of 2–D FE model.

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sliding deformations along the sliding plane were represented by 6-node joint elements (Pande et al., 1979) and assumed to be a non–linear visco-elastic body. The nodal displacements perpendicular to the right and bottom boundaries of the model were fixed at zero. All the analyses were conducted under plane strain conditions.

By applying downward gravitational force to the entire model, linear elastic analysis was conducted and the initial stress state of both the solid and joint elements was simulated. This state was regarded as time $t$ = 0 for the non-linear viscous sliding deformation analysis along the joint elements, i.e. sliding plane. This viscous sliding deformation was expressed by decreasing shear stiffness, $K_s(t)$, of joint elements with time. For the way in which $K_s(t)$ decreased, we extended the constitutive equation of variable compliance type proposed by Okubo (1992) as follows:

$$\frac{d\lambda^*(t)}{dt} = \frac{1}{t_0}\left(\frac{m}{n+1}\right)^{\frac{m}{n-m+1}} \left(\lambda^*(t)\right)^m \left(\sigma^*(t)\right)^n \text{.........(1)}$$

where $\lambda^*(t)(= K_s(0)/K_s(t))$ is normalized compliance and monotonically increasing function with time; $t_0$ is a time constant; $m$ and $n$ are degree of ductility and time-dependency of rock, respectively (Okubo, 1992); $\sigma^*(t)$ is severity representing how close the present stress state of a joint element is to a failure envelope expressed by Mohr–Coulomb failure criterion. To make the following discussion simpler, it was assumed that rock mass was homogeneous and only $K_s(t)$ changes with time while other physical properties are constants, as shown in Table 1. The upper limit of $\lambda^*(t)$, $\lambda^*_{\text{lim}}$, was set at 10000 and joint elements whose $\lambda^*(t)$ reached $\lambda^*_{\text{lim}}$ were regarded as completely fractured.

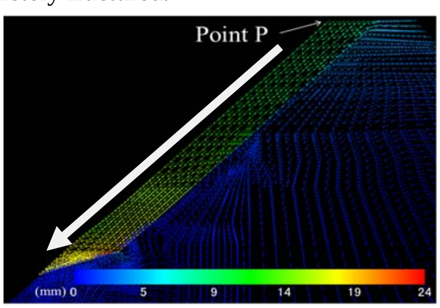



Figure 2: Distribution of viscous displacement around the rock slope at $t$ = 1 year (case A).

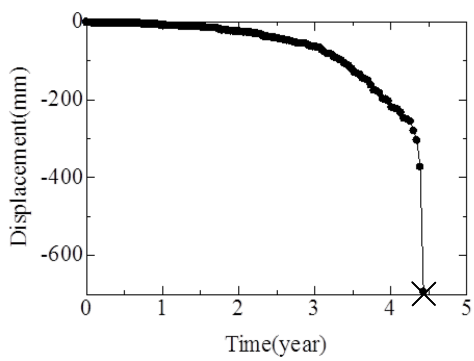
It is also important to consider the degree of deterioration of the sliding plane at the stage of construction of buttress. In this study, the following two cases were considered:

− Case A: $\lambda^*(0)$ of the entire sliding plane was set at 1.1 and $\lambda^*(t)$ increased according to equation (1).
− Case B: $\lambda^*(0)$ of the geological boundary and latent sliding plane were set at $\lambda^*_{\text{lim}}$ and 1.1, respectively, and $\lambda^*(t)$ of only latent sliding plane increased according to equation (1).

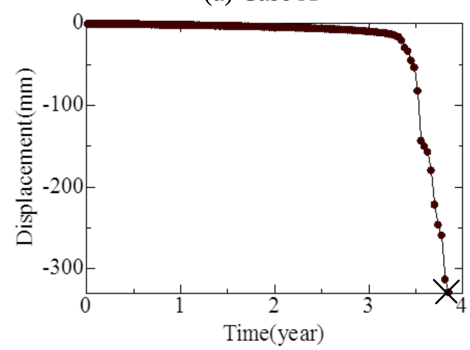
Table 1: Physical properties used in the analysis.

| Solid element (Rock mass) | Values | Joint element (Sliding plane) | Values |
|---|---|---|---|
| Young's modulus, $E$ | 1.0 GPa | Initial Shear stress, $K_{s0}$ | 3.4 MPa |
| Poisson's ratio, $\nu$ | 0.25 | Normal stress, $K_n$ | 1.0 MPa |
| Unit weight, $\gamma$ | 27.0 kN/m$^3$ | Cohesion, $c$ | 0.7 MPa |
| | | Friction angle, $\varphi$ | 50° |

To demonstrate that the inelastic time-dependent sliding deformation of rock slopes can be successfully simulated by the proposed approach, an example of the analytical results for case A is shown in Figure 2. This figure shows the distribution of viscous displacement around the rock slope between $t$ = 0 and 1 year. It was found that rock mass above the entire sliding plane showed obliquely downward sliding relative to the sliding plane. Case B was also found to show the same tendency.




(a) Case A




(b) Case B

Figures 3 : Temporal change of horizontal viscous displacement at point P in Figure 2. Time at "×" represents $t_{\text{life}}$.

Figures 3(a) and (b) show the results of the temporal change of horizontal viscous displacement at the top of the mountain (point P in Figure 2) for cases A and B. It is clear that both cases first showed a gradual increase of displacement followed by a sudden increase. In cases A and B, the entire sliding plane was regarded as collapsed when $\lambda^*$ of all joint elements reached $\lambda^*_{lim}$ in about 4.5 years and 3.8 years, respectively.

From the above results, because the non-linear time-dependent sliding deformation of rock slopes along the sliding plane was successfully expressed, it is possible to discuss whether the application of rock buttress can extend the time when $\lambda^*$ of all joint elements reaches $\lambda^*_{lim}$, i.e. expected life of rock slope, $t_{life}$, by suppressing the sliding deformation along the sliding plane.

## 3. EFFECT OF ROCK BUTTRESS ON REDUCTION OF ROCK SLOPE SLIDING

### *3.1 Effect of height of rock buttress*

In order to investigate the effect of rock buttress on $t_{life}$, the model shown in Figure 4 was analyzed in which various heights of buttress, $h_{but}$ = 30 m - 130 m, with the fixed width were considered. The rock buttress was expressed by 6-node and 8-node linear elastic solid elements with Young's modulus $E_{but}$, Poisson's ratio $\nu_{but}$ and unit weight $\gamma_{but}$. In the following analyses, solid elements corresponding to the rock buttress were deactivated until $t$ = 50 s, and then activated at $t$ = 50 s. The aforementioned two cases of degree of deterioration of the sliding plane, cases A and B, were analyzed.

Figure 5 compares temporal changes of horizontal viscous displacement at the top of the slope at point P in Figure 2 with/without rock buttress for cases A and B. The physical properties of buttress were fixed at $E_{but}$ = 0.01 GPa, $\nu_{but}$ = 0.25 and $\gamma_{but}$ = 2.7 kN/m³. Both cases A and B show that $t_{life}$ with buttress is more or less long than that without buttress in the range of $h_{but}$ investigated in this study. Especially, $t_{life}$ in cases A and B became the longest when $h_{but}$ was 90 m and 110 m, respectively. Table 2 shows $t_{life}$ with rock buttress of various heights normalized by that without rock buttress. From the results of Figure 5 and Table 2, it is suggested that the degree of deterioration of sliding plane at the time of the application of rock buttress significantly affects $t_{life}$ and that optimum $h_{but}$ should exist depending on the degree of deterioration of the sliding plane. In other words, the ability of rock buttress to extend $t_{life}$ will be compromised once $h_{but}$ exceeds the optimum value.

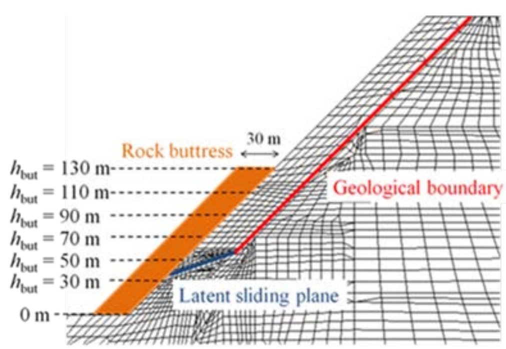
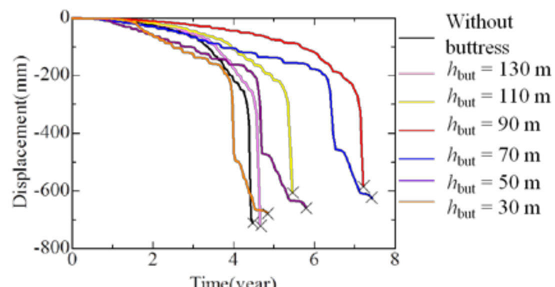


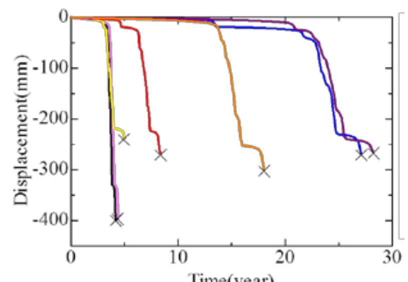

Figure 4: Various heights of buttress, $h_{but}$, analyzed in this paper.

Table 2: $t_{life}$ with rock buttress of various $h_{but}$ normalized by $t_{life}$ without rock buttress.

| $h_{but}$ | 30 m | 50 m | 70 m | 90 m | 110 m | 130 m |
|---|---|---|---|---|---|---|
| Case A | 1.1 | 1.2 | 1.6 | 1.7 | 1.3 | 1.1 |
| Case B | 1.0 | 1.2 | 2.0 | 6.4 | 6.6 | 4.2 |




(a) Case A




(b) Case B

Figure 5: Temporal changes of horizontal viscous displacement at the top of the slope (Point P in Figure 2) with/without rock buttress. Time at “×” represents $t_{life}$.

Figures 6 and 7 show the stress state on sliding plane just before and after the application of rock buttress in case where $h_{but}$ was 90 m and 110 m, which showed the longest $t_{life}$ in cases A and B, respectively (See Table 2). In these figures, black and red lines represent the stress state of joint elements before and after the application of rock buttress, respectively. Horizontal axes in these figures represent the position on sliding plane in which latent sliding plane is in from 0 m (slope surface near the toe) to 63 m (the intersection of latent sliding plane and geological boundary) and is in from 63 m to 353 m (top of slope); Compressive normal stress, $\sigma_n$, and shear stress, $\tau$, causing normal fault are expressed by negative values; absolute value of severity, $|\sigma^*|$, closer to 1 indicates that the stress state is closer to failure envelope.

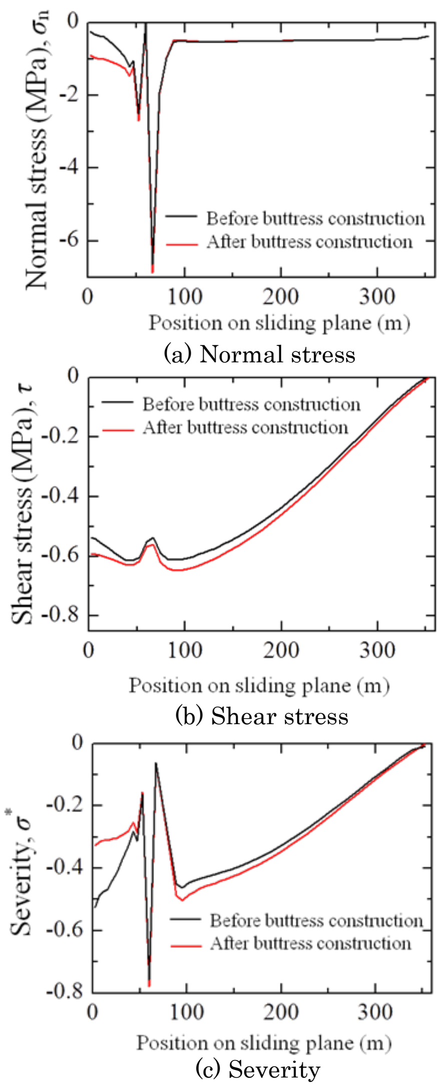



Figure 6: Change of stress states on sliding plane before and after applying buttress (Case A).

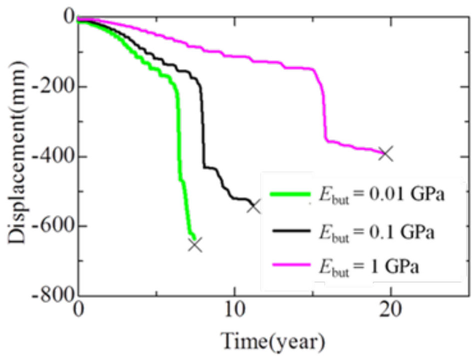
These results show that the application of rock buttress mainly affects the zone of latent sliding plane. Especially, when $\sigma_n$ pressing the latent sliding plane increased, the result was a decreasing effect of $|\sigma^*|$ in both cases A and B. $\tau$ promoting sliding deformation along the entire sliding plane in case A and latent sliding plane in case B increased, resulting in the increasing effect of $|\sigma^*|$. For $h_{but}$ investigated in this study, the increasing effect of $|\sigma^*|$ due to increase of $\tau$ along the entire sliding plane was smaller than the decreasing effect of $|\sigma^*|$ due to an increase of $\sigma_n$ of latent sliding plane. Thus, the application of rock buttress results in extending $t_{life}$. However, it is also suggested that the application of rock buttress with much larger height than those investigated in this paper should enhance $\tau$ promoting sliding deformation along the entire sliding plane and $t_{life}$ could be shorter than $t_{life}$ without the rock buttress. The process of sliding plane failure was found to progress from the toe of slope to the top of the slope.

### *3.2 Effect of Young's modulus of rock buttress*

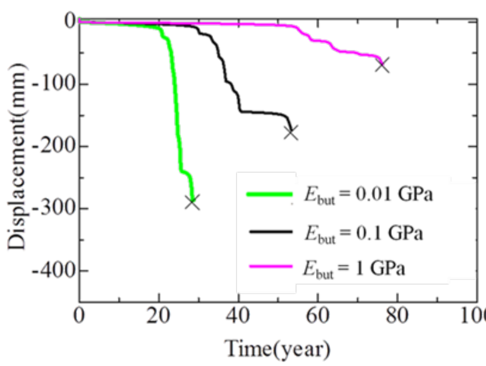
The effect of Young's modulus of rock buttress, $E_{but}$, on reduction of rock slope sliding was also investigated. Three cases, $E_{but}$ = 0.01 GPa, 0.1 GPa and 1 GPa, were analyzed only for $h_{but}$ = 90 m and 110 m in cases A and B, respectively. It is worth mentioning that the effect of Poisson's ratio, $\nu_{but}$, was also investigated in the preliminary analysis, however, the effect of the change of $\nu_{but}$ was negligible therefore this paper only discusses the effect of $E_{but}$.

Figure 8 shows temporal changes of horizontal viscous displacement at the top of the slope (Point P in Figure 2) for each $E_{but}$ in cases A ($h_{but}$ = 90 m) and B ($h_{but}$ =110 m). Table 4 shows $t_{life}$ with rock buttress for each $E_{but}$, normalized by $t_{life}$ without rock buttress. These results clearly show that the larger $E_{but}$ resulted in longer $t_{life}$. In particular, the condition of $E_{but}$ = 1.0 GPa resulted in about 18−times longer $t_{life}$ than $t_{life}$ without rock buttress and the smallest viscous horizontal displacement.

Figures 9 and 10 compare the stress state on sliding plane just after the application of rock buttress for each $E_{but}$ in cases A and B. The meaning of vertical and horizontal axes of these figures is the same as those of Figures 6 and 7. Because a relatively clear difference of the tendency between each $E_{but}$ was found only near the slope surface on the latent sliding plane, these figures only show the results for the latent sliding plane near the slope surface. Regardless of cases A and B, larger $E_{but}$ resulted in smaller $\sigma_n$ and smaller $\tau$. In case A, although only the results at latent sliding plane near the slope surface are shown in the figure, larger $E_{but}$ reduced $\tau$ promoting sliding deformation for the entire sliding plane, which significantly decreased $|\sigma^*|$. On the other hand, change of $E_{but}$ locally affected $\sigma_n$ (as in Figure 9(a)) and caused little difference for the remaining sliding plane, resulting in a local increase of $|\sigma^*|$ only near the slope surface. $|\sigma^*|$ for entire sliding plane



(a) Case A

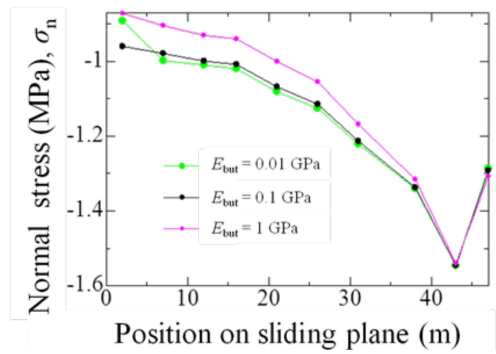


(b) Case B

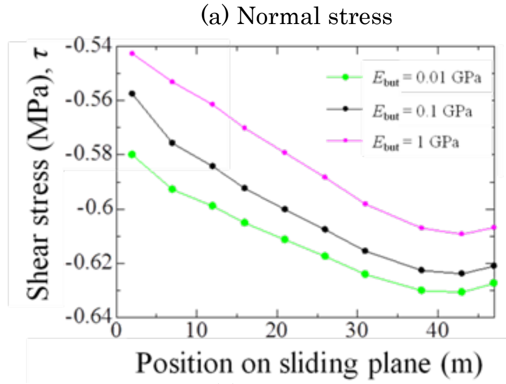
Figure 8: Effect of $E_{but}$ on temporal changes of horizontal viscous displacement at the top of the slope (Point P in Figure 2). Time at “×” represents $t_{life}$.

Table 4: Expected life of rock slope with buttress normalized by that without buttress for various $E_{but}$ in Cases A ($h_{but}$ = 90 m) and B ($h_{but}$ = 110 m)).

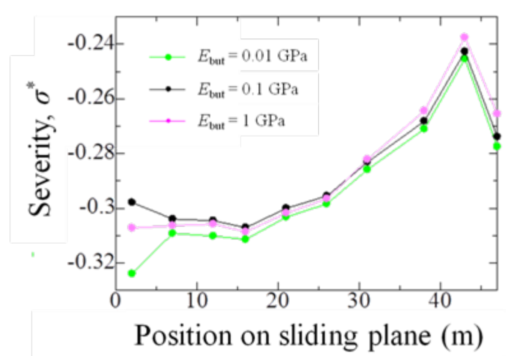
| $E_{but}$ | 0.01 | 0.1 | 1.0 |
|---|---|---|---|
| Case A ($h_{but}$=90m) | 1.7 | 2.5 | 4.4 |
| Case B ($h_{but}$=110m) | 6.6 | 12.5 | 17.9 |



(a) Normal stress

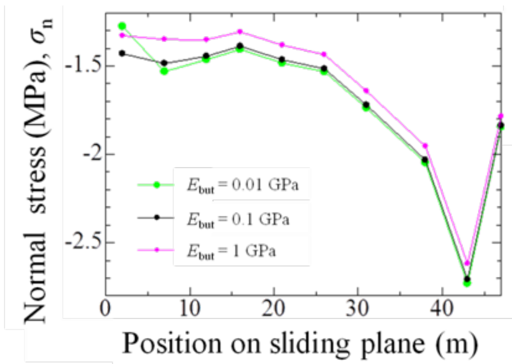


(b) Shear stress

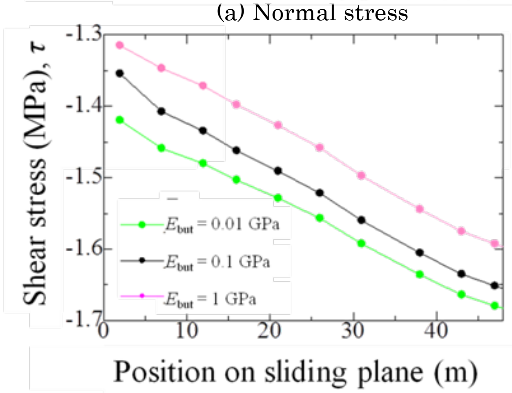


(c) Severity

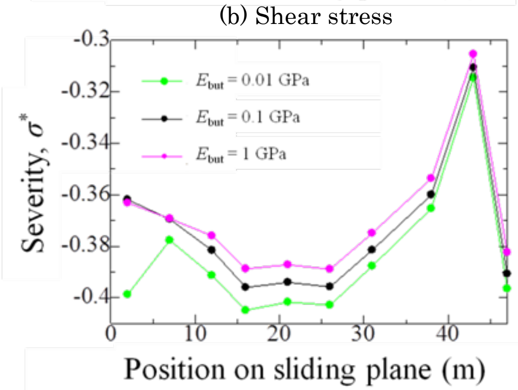
Figure 9: Comparison of stress state on sliding plane after applying buttress with different $E_{but}$ (Case A).




(a) Normal stress




(b) Shear stress




(c) Severity

Figure 10: Comparison of stress state on sliding plane after applying buttress with different $E_{but}$ (Case B).

decreased and $t_{life}$ extended. A similar explanation can be made for the results of case B.

From the above discussion, in the case of fixed $h_{but}$, it is preferable to apply stiffer rock buttress using such cement in order to effectively extend $t_{life}$.

## 4. CONCLUSIONS

In this study, non-linear time-dependent sliding deformation of rock slope along the sliding plane was analyzed by 2-D FEM, and the effect of rock buttress on reduction of the rock slope sliding was discussed.

The obtained knowledge is summarized below:

- The deterioration of sliding plane at the time when rock buttress was applied significantly affected the expected life of rock slope.

- The optimum height of rock buttress was found to exist.

- Stiffer rock buttress with larger Young's modulus resulted in the longer expected life of the rock slope.

- The balance of increase and decrease of normal and shear stresses on sliding plane by buttress is important, and the obtained results can be changed by the difference of friction angle and the geometry of the sliding plane.

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