ARMA 13-237

Mechanisms of Falling Rock Formation at Steep Slope due to Temperature Perturbation.

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This paper was prepared for presentation at the 47[th] US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA, USA, 23-26 June 2013.

ABSTRACT: To clarify the mechanisms of formation of falling rocks, a 2D finite element modeling was performed to numerically analyze natural stress development at a fracture tip for a rock mass (20 m x 20 m) with a rock beam of 3.0 m thickness and 10 m long. The cyclic temperature variations between 10 to 40^{o}C (warm region) and -10 to 20^{o}C (cold region) were assumed. In warm region, the fracture closure due to difference in thermal expansion in the rock beam was prohibited inducing a vertical bending tensile stress (σ_y) in summer while in winter, the fracture opened due to difference in thermal shrinkage in the rock beam inducing a horizontal tensile stress (σ_x) at the fracture tip. In the cold region σ_y was also observed in winter due to fracture closure by difference of freezing expansion in the rock beam was observed. The σ_x developed during both regions were large enough for the fracture propagation. The repeated occurrence of σ_y would result in breakage of the rock beam from its bottom by either subcritical or fatigue crack growth ensuing a rock fall at a steep rock slope.

1. INTRODUCTION

Fracture in steep rock cliffs can grow due to the thermal deformation, weathering, intrusion of plant roots etc, and rock beam can be formed [1-4]. Negishi and Nakajima (1994) explained toppling failure of columnar joints at Sounkyo Japan by thermal deformation and rocks trapped in the joints [5]. This is however a special case and general reason for rock beam detachment from rock cliff which leads to rock fall has not been clarified yet.

The objectives of this study are to clarify thermal stress behavior by which the vertical fracture is extended, a mechanism of the breakage of rock beam from its bottom and the influence of beam size in temperate region for a steep rock slope.

The stress development occurred at the fracture tip of the steep rock slope due to the cyclic air temperature variation in warm and cold temperate regions with influences of insulation conditions and beam size on those will be shown.

2. NUMERICAL MODEL

A 2D finite element modeling was performed to numerically analyze natural stress development at a fracture tip for a rock mass (20 m x 20 m) with a rock beam of 3 m thickness and 10 m long (Figures 1 and 2). This 2D plane strain analysis is coupled with the fundamental heat transfer equation using the Crank-Nicolson method [6].

Cyclic air temperature variations in temperate region between 10 to 40^{o}C (warm region case) and -10 to 20^{o}C (cold region case) for a duration of 2 years were assumed (Figure 3). The insulated condition was basically assumed in which the heat flux was possible only via the vertical cliff surface at 3 W/(m^{2}K) simulating thick soil or deep snow during winter. The uninsulated condition in which heat flux was possible via both cliff surface and the top of the steep rock slope was also considered. Insolation and radiation were not considered.

Table. 1. Physical, mechanical and thermodynamic parameters used in the analysis.
[a] assumed; [m] measured; [*]2 is used because of plane strain analysis.

Property	*Symbol*	*Value*	*Formula*
Young's modulus	E	110 (GPa) [m]	
Poisson's ratio	ν	0.2 [a]	
Thermal conductivity	K	7.40 (W/ m K) [m]	
Specific heat	c	995 (J/ kg K) [m]	
Density	ρ	2636 (kg/m^3) [m]	
Expansion coefficient	α	7.94×10^{-6} (K^{-1}) [a]	
Effective porosity	η	0.8% [m]	
Volumetric ice expansion due to freezing	ε_v	9% [a]	
Linear expansion strain due to freezing	ε_f	0.00036 [a]	$\sim(\eta \times \varepsilon_v)/2^*$
Temperature at which freezing starts	T_1	0 ^{o}C [a]	
Temperature at which freezing finishes	T_2	–20 ^{o}C [a]	

Physical, mechanical and thermodynamic parameters shown in Table 1 are used assuming a steep cliff consisting of chert. It was assumed that rock expands by ε_f from T_1 to T_2 due to freezing of pore water, where T_1 is the temperature at which freezing starts; T_2 is the temperature at which freezing completes (Figure 4).

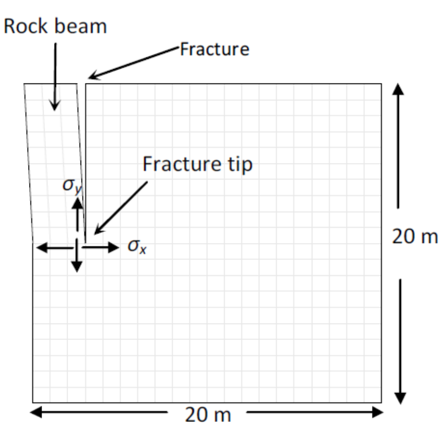


Fig. 1. Model showing rock mass (20 m x 20 m) with 10 m rock beam.

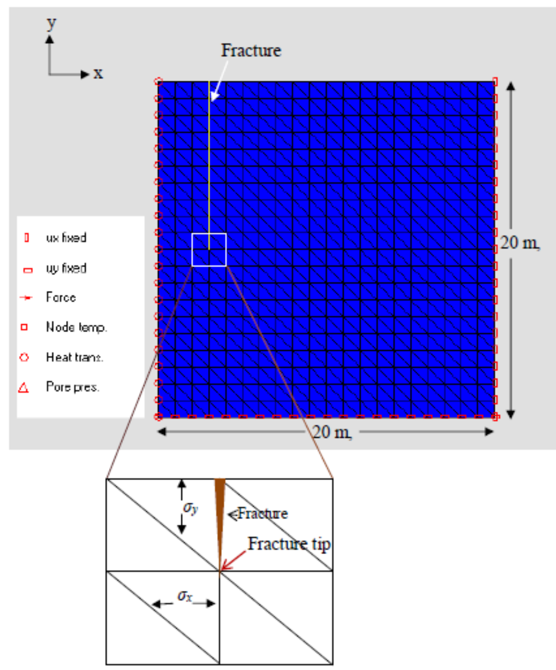


Fig. 2. Finite elements mesh configuration and Element where stress values are examined.

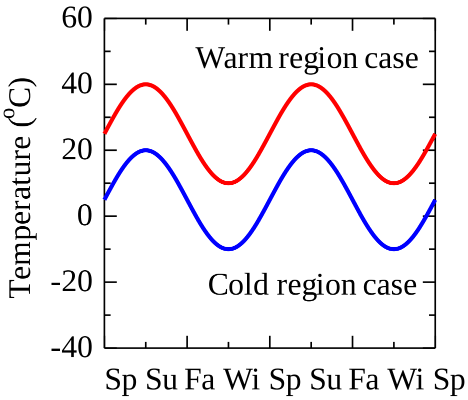


Fig. 3. Cyclic air temperature variations.

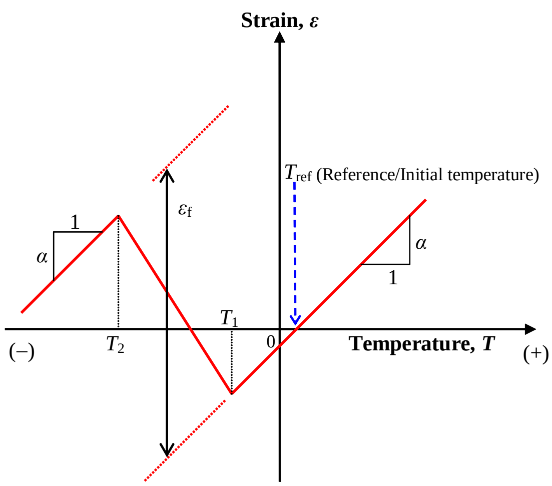
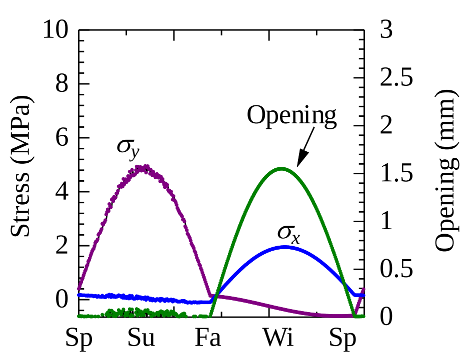
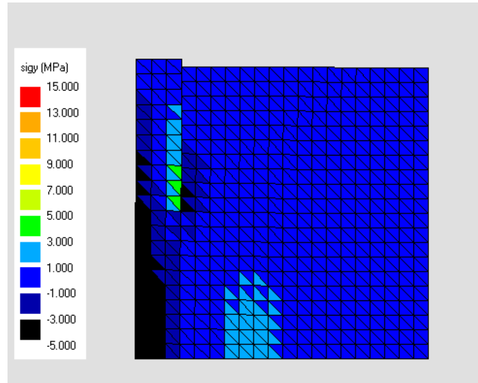


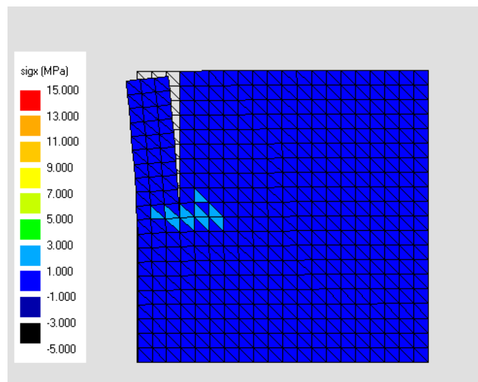
Fig. 4. Model for expansion due to freezing of pore water.



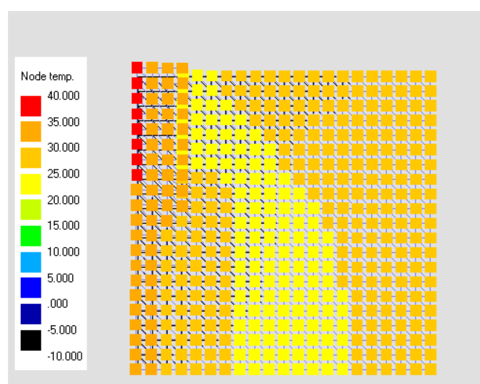
(a) Stresses at the fracture tip and fracture opening and closure with time.



(b) Fracture closure/deformation and σ_y distribution in summer.



(c) Fracture opening/deformation and σ_x distribution in winter.

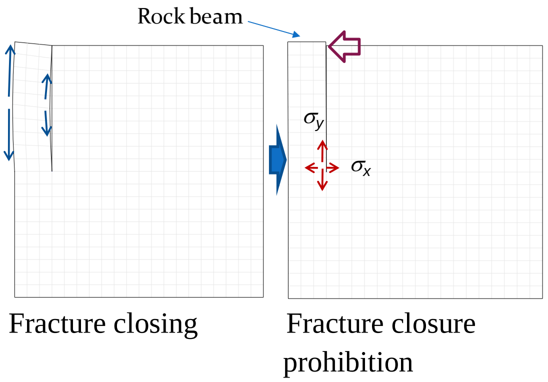


(d) Temperature distribution when σ_y maximum in summer.

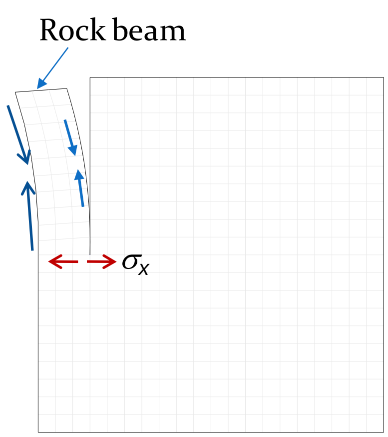
Fig. 5. Numerical result for 20 m x 20 m warm region.

3. RESULTS

a. Warm region case (Figure 5)
During summer, a vertical bending tensile stress (σ_y) appeared due to the fracture closure prohibition that occurs as a consequence of the thermal expansion difference of the rock beam (Figure 6a).



(a) Fracture closure prohibition and the stress development at the fracture tip.



(b) Fracture opening due to the shrinkage difference.

Fig. 6. Mechanism of thermal deformation.

σ_y showed a gradual increase up to its maximum (4.9 MPa) and thereafter decreased gradually. The highest temperature gradient in the rock beam with respect to the air temperature variation was observed at maximum σ_y (Figure 5d). The observed horizontal tensile stress (σ_x) was minute. The repeated occurrence of σ_y development at the fracture tip will result either subcritical or fatigue crack growth ensuing a breakage of the rock beam from its bottom.

During winter, a fracture opening was observed inducing a horizontal tensile stress (σ_x) at the fracture tip. σ_x develops with the fracture opening due to the shrinkage difference between outer strip and the inner strip (Figure 6b).

σ_x gradually increased with the fracture opening, reached its maximum (1.9 MPa) and thereafter showed a gradual decrease. The observed σ_y was minute. σ_x are large enough for the fracture propagation forming the rock beam. The stresses are larger in the uninsulated condition (Figure 7a).

b. Cold region case (Figure 8)
During both summer and winter, the vertical bending tensile stress (σ_y) was developed at the fracture tip due to the thermal or freezing expansion of the rock beam and a fracture closure prohibition (Fig. 6a). The maximum σ_y is 5.4 MPa and the repeated occurrence of this stress development at the fracture tip will result either subcritical or fatigue crack growth ensuing a breakage of the rock beam from its bottom.

In winter σ_x behaved a little bit complicated but the peak value was almost the same as in the warm region case and was large enough for fracture propagation. σ_x and σ_y in summer were larger but σ_y in winter was slightly smaller in the uninsulated condition (Figure 7b).

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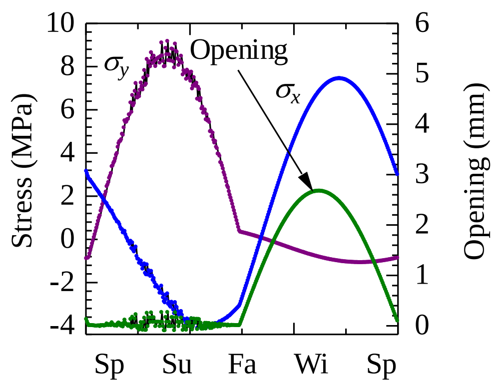
4. EFFECT OF BEAM SIZE ON THE STRESS DEVELOPMENT

a. Warm region
The vertical bending tensile stress (σ_y) was observed during summer while the horizontal tensile stress (σ_x) was observed during winter.

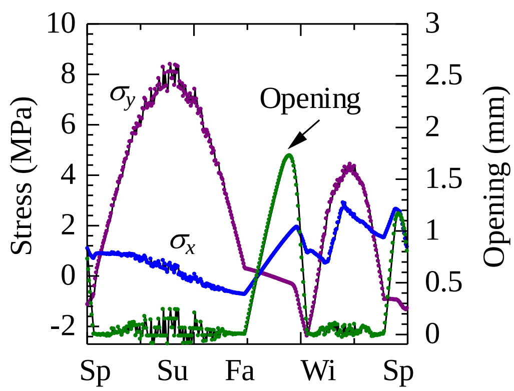
The maximum vertical bending tensile stress (σ_y) showed a gradual increase with increasing beam size and reached its maximum at a beam length and thickness of 20 m and 6 m respectively. Thereafter, σ_y decreased.

σ_x was comparatively lower than σ_y . σ_x showed a gradual increase with increasing beam length, reached its maximum value at a beam length of 32 m and decreased (Figure 9a).

These behaviors were observed because the maximum temperature gradient reached around beam size of 20-32 m for the used parameters and temperature variation. The significant decrease of σ_y was due to the overburden pressure.



(a) Warm region.



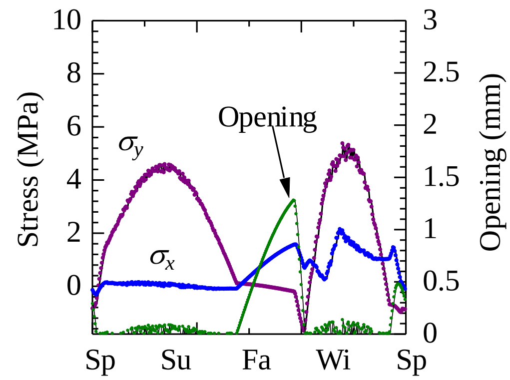
(b) Cold region.

Fig. 7. Stresses at the fracture tip and fracture opening and closure with time.

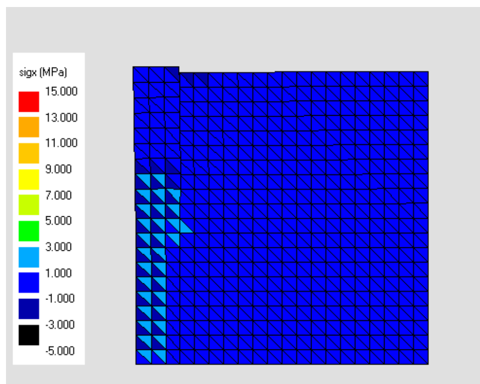
b. Cold region

The vertical bending tensile stress (σ_y) was observed during both summer and winter while the horizontal tensile stress (σ_x) was observed only during winter.

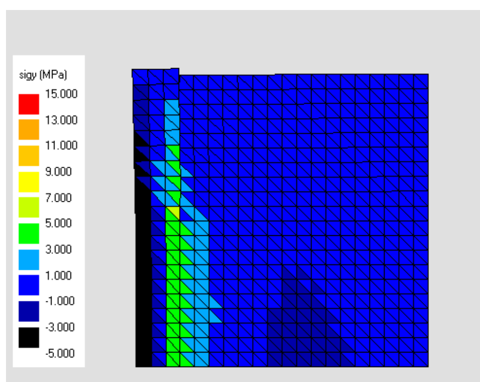
The σ_y developed up to a beam length of 6 m was dominant during winter. σ_y in summer and σ_x behave in a similar way as for warm region. The maximum σ_x was however at beam length of 9 m (Figure 9b).



(a) Stresses at the fracture tip and fracture opening and closure with time.

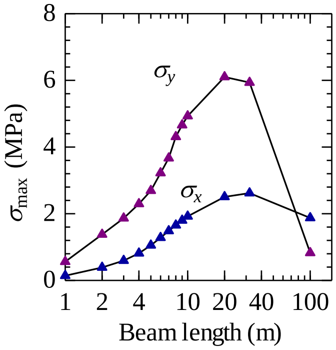


(b) Fracture closure/deformation and σ_x distribution in summer.

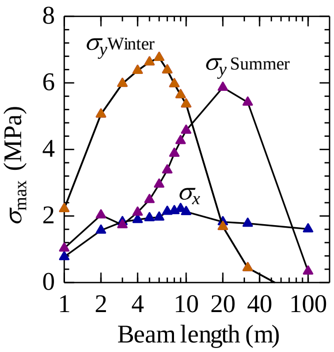


(c) Fracture opening/deformation and σ_y distribution in winter.

Fig. 8. Numerical result for 20 m x 20 m cold region.



(a) Warm region.



(b) Cold region.

Fig. 9. Maximum stress with beam length for fixed length to thickness ratio at 10/3.

5. CONCLUDING REMARKS

2-D FEM stress analyses considering thermal deformation including freezing expansion for steep cliffs subjected to cyclic air temperature change in temperate region were carried out to clarify the mechanisms of falling rock formation. The key point of the analyses is that it considers freezing expansion.

It was already known that the cyclic air temperature change in temperate regions could induce tensile stress under which rock fractures can grow. The analyses in this paper further quantitatively showed the magnitude of the tensile stress and its variation with the rock beam size.

This paper also newly clarified the followings mainly on the mechanisms by which falling rock blocks are formed.

(i) Vertical bending tensile stress can develop and repeated occurrence of the stress can break the beam from its bottom.

(ii) The vertical bending tensile stresses in summer and horizontal tensile stress are larger when heat transfer from the top is not insulated.

(iii) The stresses show peaks at specific beam sizes which depend on thermal and mechanical properties of rock mass and weather conditions.

Numerical investigation on the influences of the properties and weather conditions on the beam sizes at which the stress peaks are shown and field investigations on the specific beam sizes which may control the falling rock size with joint spacing will be carried out further.

The results shown in this paper as well as results in future will help deeply understand the mechanisms of rock falls and reduce human and economical damages by them.

6. REFERENCES

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