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STUDY ON MECHANISM OF ROCK FALL AT TUNNEL CUTTING FACE AFTER BLASTING

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There are around 10 casualties due to rock-fall at cutting face annually in conventional tunnel construction in Japan. As from the analysis conducted on the cases involving such casualties, workers were either killed or seriously injured when they works in front of or near the cutting face. For the purpose of evaluating the mechanism of rock fall at tunnel cutting face, this paper performed experimental tests which involved blasting to excavate a model ground of tunnel cutting face, and then analyzed the stress state which is in the cutting face by using Discrete Element Method (DEM) simulation. Based on the results, the tensile stresses remained even when the action of gas expansion due to blasting has completed. Therefore, it is suggested that rock falls might be induced because of the residual tensile stresses. The tensile stresses would gradually open small cracks between rocks and then rocks may suddenly fall after sufficient crack opening due to gravity.

Keywords: Tunnel construction, Blasting, Experimental test, DEM.

1 INTRODUCTION

Rock-fall events that occur in cutting face during conventional tunnel construction cause one to two fatalities per a year in Japan. Rock-fall happens when workers insert detonators and explosive materials into boreholes at cutting face and mount a steel arch support on a lateral side of the face. Conventional tunnels are usually excavated using explosive materials, and they would cause stress relaxation around tunnel face. According to Hino (1654), in general, the explosion of explosive materials generates shock waves that cause cracks between rocks (*The Hopkinson effect*), and then the gas generated by reaction of the materials expands the cracks between rocks; the rock ground is finally excavated by both the effects of shock waves and gas expansion. Then, stress surrounding excavated surface would be re-arranged and, some of rock loosened, during this process of stress re-arrangement, may fall in following construction works. It is very important to consider the stress state of the cutting face in terms of the actions of shock waves and gas expansion in order to reveal the mechanisms of rock-fall and to prevent it. In this study, we used a miniature detonator and investigated the stress behavior surrounding cutting face after blasts in miniature model ground. It is noted that the miniature detonator would have the action of gas expansion rather than that of shock wave because the amount of materials are so small. So we focus more on the stress state after blasting rather than during the process of blasting. For this aim, we performed not only experimental investigations but also analytical simulation to evaluate the stress post-excavation behavior. In the experimental investigation, we performed the blasting test to excavate a model ground of tunnel cutting face, made of cemented granular material. In the analytical simulation, the discrete element method (DEM) was selected to simulate the experimental blasting excavation tests.

2 EXPERIMENTAL PROCEDURE

In this study, the miniature model ground of tunnels were excavated using miniature detonators at its tunnel cutting face that was expressed as a tunnel longitudinal section inside the rectangular soil container. In order to apply sufficient earth pressure to the tunnel model even miniature, the experimental tests were carried out not only in the gravitational field (1 G) but also in the centrifugal field (50 G) and stress state before and after blasting were evaluated. In addition, these experiments were simulated using the discrete element method (DEM) in order to estimate the stress state distribution surrounding the cutting faces.

The specimen was prepared that Toyoura sand (silica sand) bonded with a liquid agent as we called "*cemented granular material*." The solid density, maximum and minimum void ratios of Toyoura sand are 2650 kg/m^3, 0.985, and 0.611, respectively. The concentration of the liquid agent is 10% in the silica content. The results of the uniaxial compression test of the specimen using the same ground are shown in Figure 1.

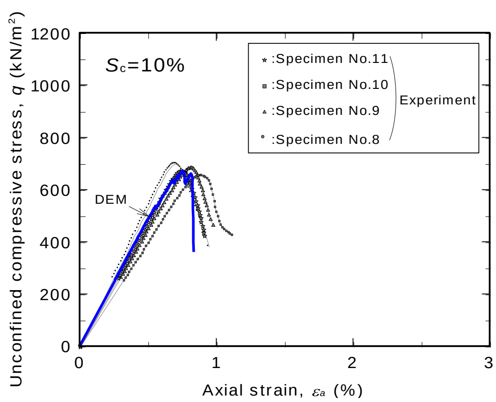


Figure 1. Stress-strain behavior of cemented granular material in uniaxial compression test and its simulation by Discrete Element Method (DEM).

The uniaxial compressive strength of cemented granular materials was about 680 kN/m^2. P- and S-wave velocities of the material are obtained as V_p= 880 m/sec, V_s= 291 m/sec, respectively, from bender/extender element tests (Kikkawa *et al.* 2013). In general, the elasticity wave velocity of soft rocks is ranging from 700 to 2800m/sec, it satisfies the requirement of soft rock from P-wave velocity, but uniaxial compressive strength shows lower value than soft rock.

2.1 Procedure of Blasting Test

In this study, the model ground was dimensioned as shown in the Figure 2. The cutting face of the ground was excavated using miniature detonators. Each to 21 boreholes that were 20 mm depth in the cutting face inserted the miniature detonators, and then those boreholes filled with Toyoura sand and sealed with an instantaneous adhesive. After completing the preparation of tests, we applied voltage to miniature detonators and then the cutting face was excavated approximately 20 mm in the tunnel progress direction.

2.2 Procedure for Discrete Element Method Simulation

We used the three-dimensional particle flow code (PFC3D, Itasca Consulting Group Inc. 2008) to simulate the blasting test. We installed parallel-bonds at the contacts between the spherical solid elements in order to simulate the cemented granular material. The parallel-bond can resist not only normal and tangential stresses but also the moment. The stiffness of the spherical element and the parallel-bond were determined using the P- and S-wave velocities of the Toyoura sand itself (relative density: D_r= 80%, void ratio: e= 0.686) and the Toyoura sand bonded by the liquid agent. We measured both elastic wave velocities using bender/extender element tests (Kikkawa *et al.* 2013). The strength of the parallel-bond was determined from the unconfined compression strength of the cemented granular material. The model ground on simulation was dimensioned as shown in the Figure 2, it is the same as the experimental tests.

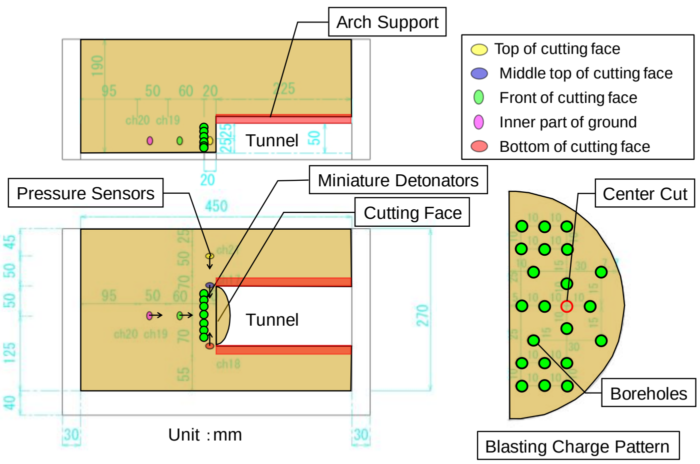


Figure 2. Schematic drawings of model ground of tunnel.

The maximum radius of the sphere element, R_{max}, is 5 mm, and the ratio of maximum and minimum radii, R_{max}/R_{min}, is 2 with a mean radius, R, of 3.75 mm. Determination manner of the parameters of spherical element and parallel-bond is detailed in reference (Kikkawa et al 2013). It can be confirmed that the stress-strain relationship by simulation of the uniaxial compression test using the parameters selected by the determination manner corresponded well the experimental results as shown by the line in Figure 1. Miniature detonators have two actions: one is the action induced by expanding gas and the other is the action induced by stress waves. The miniature detonator amounted to only 40~50 milligrams, so it is assumed to be more effective in the action of expanding gas rather than that of stress wave. In this study, we focused more on the stress state of the cutting face after blasting. In the DEM simulation, a spherical rigid wall expands and contracts as increasing and decreasing the diameter of the wall constantly in order to express the action of expanding gas. The position of the spherical walls was the same as that of the detonators used in the experimental tests. The initial radius of the spherical walls was 1 mm. The initial radius of the spherical walls of 1 mm expands to a maximum radius of 5 mm at a rate of 35 mm/sec. After that, the radius of the spherical walls contracts to a minimum radius of 1 mm at the same rate. The values of the maximum radius of the spherical walls, the expanding and contracting rates were determined from the results of parametric studies between the experimental blasting test of a cylindrical specimen using one miniature detonator and its DEM (Kikkawa *et al.* 2014).

3 RESULTS AND DISCUSSION

The stress measured against elapsed time is shown in Figure 3 (1 G field) and Figure 4 (50 G field). The upper part of the figure is the enlarged view of its relationship. In these figures, the positive value shows the compressive stress. As seen in these figures of both the 1 G and 50 G field, stress rapidly increases close to 0.044 sec that the action of gas expansion would arrive to each pressure sensors.

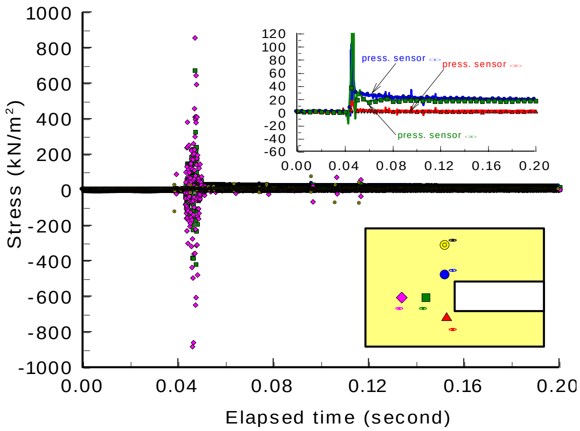


Figure 3. Stress against elapsed time in 1 G field.

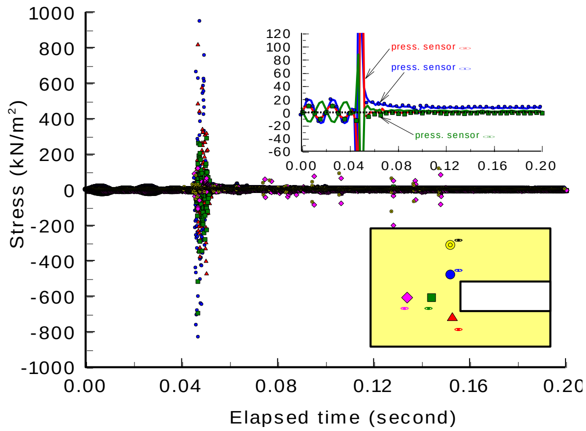


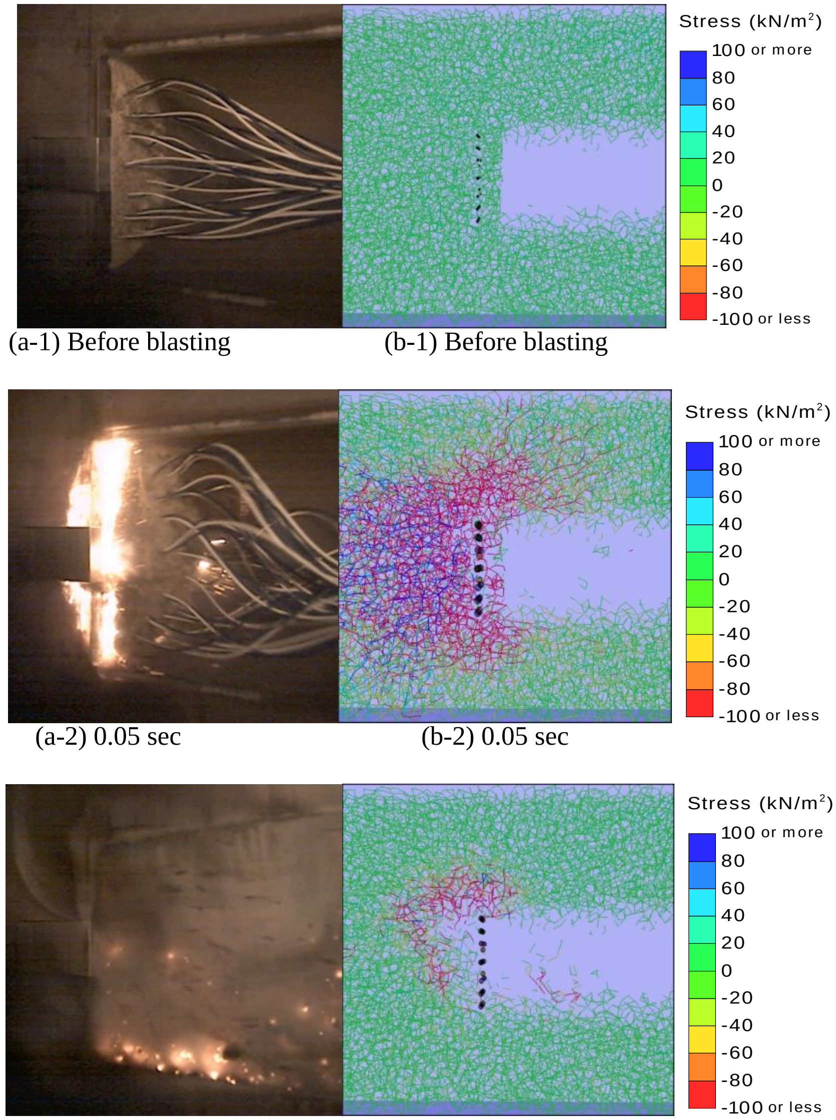
Figure 4. Stress against elapsed time in 50 G field.

In the 1 G field, the arrival of elastic waves is also observed around 0.040 seconds, but in 50 G field, the arrival of elastic waves is not clear due to the influence of noise. Behavior like a wave from 0 seconds to 0.04 seconds at 50 G field would be an electric noise. There is a possibility that an earth wire would not be mounted correctly during the experiment.

On the other hand, as looking at the elapsed time of 0.20 sec, compressive stress of 19 kN/m^2 remained in the middle top part of the face in the 1 G field. Since the pressure due to blasting (1000 kN/m^2 or more) is larger than the uniaxial compressive strength (about 680 kN/m^2) of the ground, it is considered that the ground was compressed and deformed. However, at 50 G field, the residual compressive stress of the middle top part of the cutting face is smaller and the stress approaches to 6 kN/m^2 asymptotically. This is supposed to the effect of overburden pressure because the initial overburden pressure is larger at the 50 G field than at 1 G field, so stress decreased much more after blasted at the 50 G than at 1 G field.

Images by high-speed camera and the distribution of stress acting on the parallel-bonds by the simulation are shown in Figure 5 (1 G field) and Figure 6 (50 G field). After 0.05 seconds, it can be confirmed that the cutting face is excavated by the action of the miniature detonator. We measured the excavation length of the tunnel progress direction from the cutting face that was about 20 mm on both experiments, so it was possible to satisfy the target excavation length. On the distribution of the stress acting on the parallel-bonds by the simulation, even after the expansion and contraction of the spherical rigid walls has completed (elapsed time of 0.2 seconds), tensile stresses remained at the bond from the top to the front of the cutting face.

As considering stress distribution after blasted in a cutting face of actual conventional tunnel construction, tensile stress remains inside the excavated surface as described above. So it is supposed that the tensile stress gradually open small cracks between rocks and then rocks may suddenly fall after sufficient crack opening due to gravity.



(a-1) Before blasting (b-1) Before blasting

(a-2) 0.05 sec (b-2) 0.05 sec

(a-3) 0.20 sec (b-3) 0.20 sec

Figure 5. Images of tunnel cutting face and its simulation in 1 G field
(a) Images of tunnel cutting face by high-speed camera; (b) Stress distribution acting on the parallel-bonds

4 CONCLUSIONS

This paper performed experimental tests that involved blasting to excavate a model ground of tunnel cutting face and then analyzed the stress state in the cutting face by using Discrete Element simulation. Based on the results the tensile stresses remained even when the action of gas expansion due to blasting has completed. Therefore, it is suggested that rock falls might be induced because of the residual tensile stresses. The tensile stresses would gradually open small cracks between rocks and then rocks may suddenly fall after sufficient crack opening due to gravity.

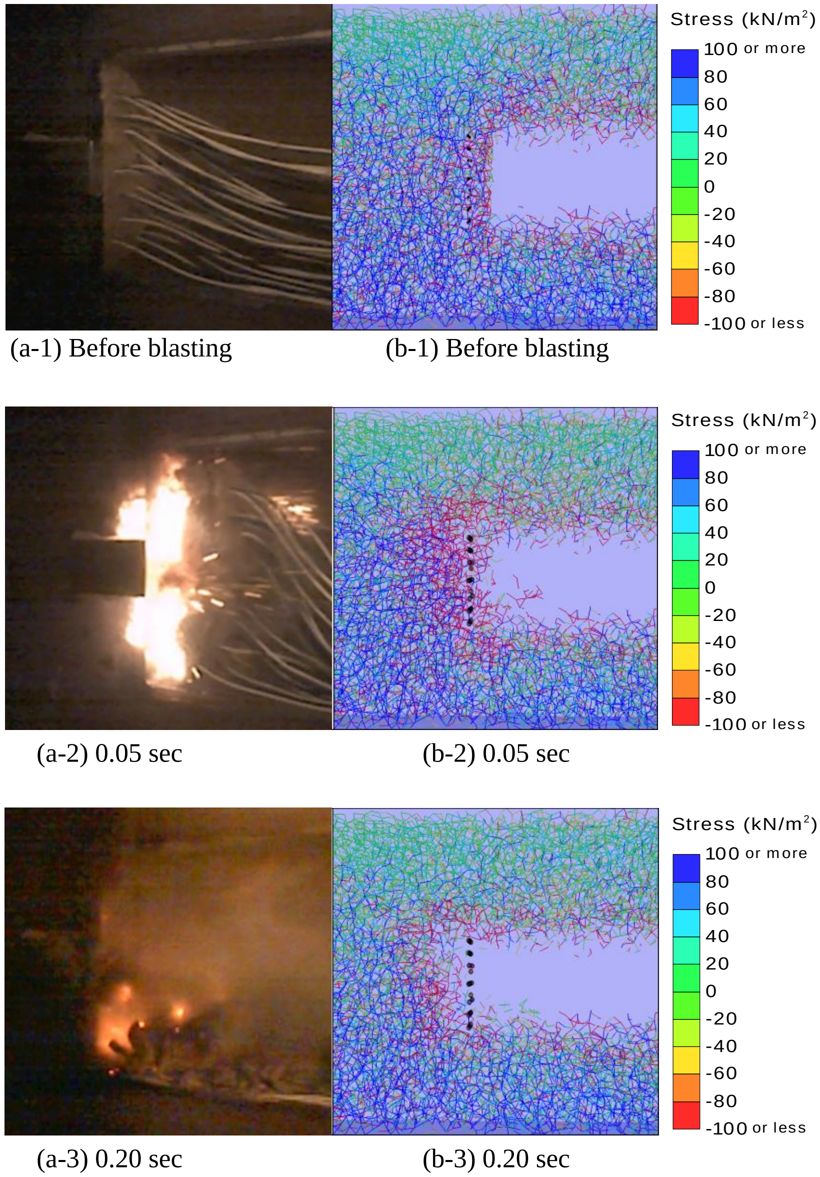


Figure 6. Images of tunnel cutting face and its simulation in 1 G field
(a) Images of tunnel cutting face by high-speed camera; (b) Stress distribution acting on the parallel-bonds.

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