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A REVISITING OF PHOTO-ELASTICITY TECHNIQUE AND ITS RENEWED POTENTIAL USE IN ROCK MECHANICS AND ROCK ENGINEERING

Ömer AYDAN[1*]

[1]University of the Ryukyus, Dept. of Civil Engineering, (1 Senbaru, Nishihara, Okinawa, 903-0213, Japan)
**E-mail: aydan@tec.u-ryukyu.ac.jp*

Photo-elasticity used in various engineering fields in the past to investigate the stress concentrations and it is the only method to visually observe stresses. However, this technique receives less attention nowadays due to the advances of numerical techniques as well as computational technology. The author utilized this technique to study the stress variations and distributions by considering typical conditions of slip of faults, discontinuities, slopes, foundations and underground openings in continuum and discontinuum. The author reports the outcomes of preliminary results and discusses their implications in rock mechanics and rock engineering.

Key Words : *Photo-elasticity, model, stress distribution, education, fault.*

1. INTRODUCTION

Photo-elasticity used in various engineering fields in the past to investigate the stress concentrations since its invention in 1815 by Brewster and it is formulated by Fresnel in 1820 to establish relation between phase difference of lights and maximum shear stress acting within the object subjected to some tractions along its boundaries (Frocht, 1965). This is the only method to visually observe stresses and it served well in various field of engineering including Rock Mechanics and Rock Engineering. However, this technique receives less attention nowadays due to the advances of numerical techniques as well as computational technology. However, the computational results from numerical techniques may still require some validation by this technique particularly in fracturing and/or dynamic problems. Furthermore, the validation of computational codes for simulating the behavior of discontinuum is especially necessary. The remote-sensing techniques of airborne or space are also fundamentally based on the principles of photo-elasticity although the laser beams such as SAR, LIDAR, DInSAR are used.

The author has been utilizing this technique to study the stress variations and distributions by considering typical conditions of slip of faults, discontinuities, slopes, foundations and underground openings in continuum and particularly in discontinuum. The author describes the outcomes of preliminary results. The author also discusses their implications in rock mechanics and rock engineering and its renewed potential both for educational and research purposes in view of advances in digital recording and processing of data and LED technology.

2. PRINCIPLE OF PHOTO-ELASTICITY AND DEVICES

The invention of photo-elasticity technique is attributed to Brewster (1815) while Fresnel (1820) was the person to formulate the phase delay Δ to the maximum shear stress acting in a stressed body with a given thickness *t*, which related to the phase retardation (Figure 1). This relation is given in the following form:

$$\Delta = \frac{2\pi t}{\lambda} C\left(\sigma_1 - \sigma_3\right) \qquad (1)$$

where C is photo-elasticity coefficient, λ is vacuum length and σ_1 , σ_3 are principal stress components. A fringe pattern appears due to optical inference of waves. The number of fringe order N is related to retardation factor as

$$N = \frac{\Delta}{2\pi} \qquad (2)$$

One can determine the state of stress at various points in the material from fringe patterns.

The actual photo-elasticity devices are quite large and expensive requiring a light-source with well-known characteristics. However, it is quite difficult to find light sources commercially available in Japan while one can easily gets them from some other countries such as India, China and USA in nowadays.

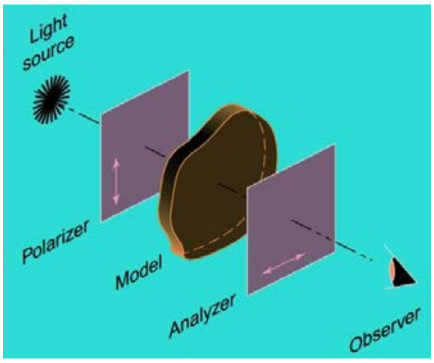


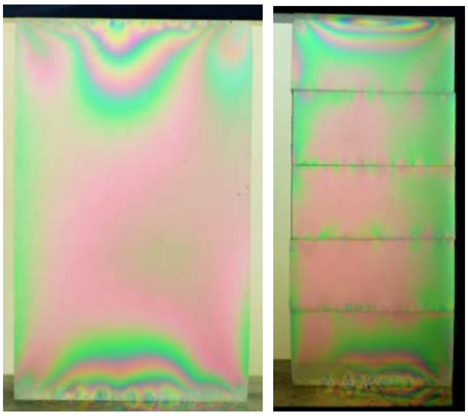
Figure 1. Principle concept of photo-elasticity devices

Originally polariscopes, which are based on photo-elasticity principle, are developed for showing the stress distributions and concentrations in relation to educational purposes. It is also possible to produce hand-made polariscopes utilizing LED lights, polarizer films while digital cameras with circular polar lenses can be used as an analyzer and to take static and dynamic images (Figure 2). The author produced such a system for photo-elasticity experiments and the outcomes of these studies are presented in the next sections.

Figure 2. Implementation of photo-elasticity principle in practice.

3. PHOTO-ELASTICITY TESTS

In this section, several examples of practical applications are presented. The examples are directly involved with some laboratory experiments and field examples encountered in Rock Mechanics and Rock Engineering. Models were made of polyurethane or gelatin. Gelatin was used to study the failure phenomenon of structures while elastic stress distributions are studied using samples made of polyurethane.


(a)Continuum (b) Layered Medium
Figure 3 Stress distributions in continuum and discontinuum subjected compression

3.1 Continuum and Discontinuum Samples Subjected to Uniaxial Compression and Brazilian Tests

Compression experiments are often used to determine mechanical properties of rock and rock masses. Figure 3 shows two examples of compression experiments sandwiched between two relatively rigid loading plates. As noted, stress distribution is not uniform and some stress concentrations occur near the interface between loading plate and sample. Although this difference is often attributed to friction, it is fundamentally due to difference between the deformation modulus of loading platens and that of samples (Aydan et al. 2016). Regarding the discontinuum (layered) model, some local stress concentrations occur at the discontinuity planes in addition to that caused by deformation modulus difference between loading platens and samples.

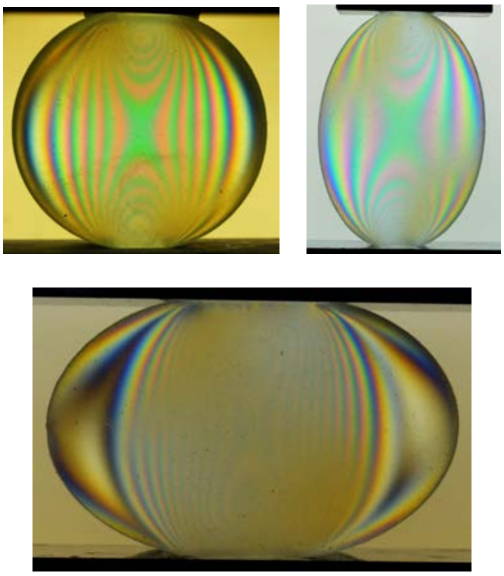


Figure 4. Stress distribution in circular and elipsoidal samples subjected to diametrical compression (Brazilian test)

Next, stress distributions on samples subjected to Brazilian type tensile strength tests are investigated using circular and elipsoidical shaped samples. (Figure 4) Particularly, elipsoidical samples may have some relevance to point load experiments. Despite the difference between shapes of samples, stress distributions resemble to each other and the point-load experiments may have direct relations to the tensile strength of rock samples.

3.2 *Discontinuities*

Discontinuities play great role on the behavior and stability of rock masses. A sample having a discontinuity plane consist of regular asperities with a 30 degrees inclination as shown in Figures 5 and 6 is subjected to normal load only and a combined shear and normal loading together with a relative slip. As noted from Figures 5 and 6, the existence of discontinuity plane plays a great role on the overall stress distribution. Furthermore, the slip results in high compression on contact side and tensile stresses on separated side of asperities. This result may also important implications on the visualization of asperity models commonly used in earthquake science for simulating strong motions.

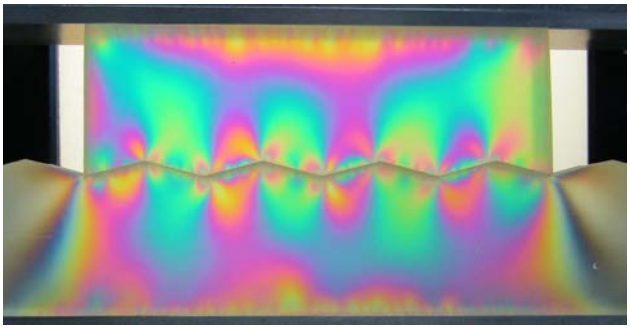


Figure 5. Stress distribution of a sample of regularly spaced asperities under normal loading only.

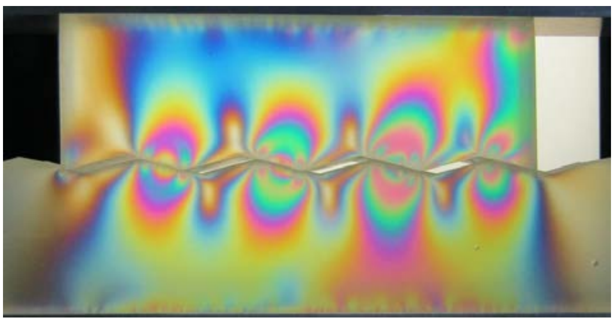


Figure 6. Stress distribution of a sample of regularly spaced asperities under combined normal and shear loading.

Stress distribution in the vicinity of fault-like discontinuity plane in a continuum model subjected to dextral fault type boundary conditions is studied as shown in Figure 7. The surface configuration of the fault-plane was relatively rough. As noted from the figure, Stress concentrations occur at the tips of the fault plane while symmetric stress shadows occur in the central parts on the both sides of the fault plane.

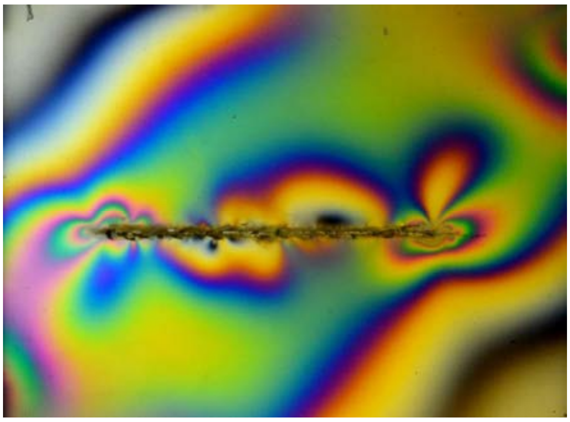
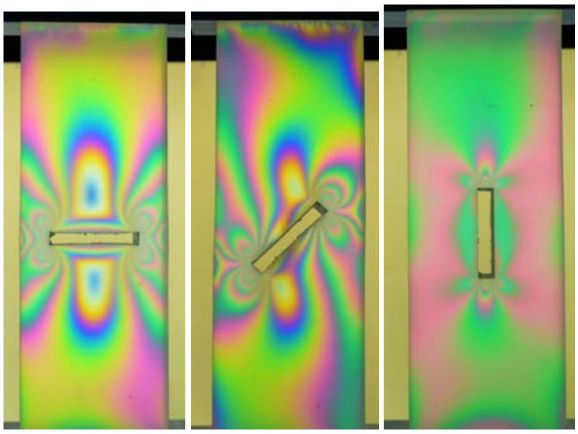


Figure 7. Stress distribution in the vicinity a model fault plane subjected to dextral type fault boundary conditions.



(a) 0 degree slit (b) 45 degree slit (c) 90 degree slit

Figure 8. Stress distribution in samples having slits with different orientations

3.3 *Samples with Slits*

Samples having slits are often used to study the effect of distributed cracks on the overall behavior of rocks. For this purpose, samples having a slit having its longitudinal axis oriented to 0, 45, 90 degrees from horizontal prepared and subjected to different loading regimes as shown in Figure 8. As noted from the figure, stress distributions in samples are quite different depending upon the orientation of the longitudinal axis of the slit. While the effect of 90 degree slit is less, the stress concentrations occur at the tip of the slit and tensile stresses occur near the central part of the slits for samples having 0 and 45 slits.

3.4 Footing and Socket-like Foundations

The foundations of spread type footing or socket-like foundations are quite common in rock engineering applications. Furthermore, the existence of discontinuities greatly affect the stress distributions and their resistance (e.g. Gaziev and Erlikhman, 1971; Maury 1969). Figures 9 and 10 show the stress distributions of spread-type footing and socket-like foundations subjected to compression. As shown in Figure 9, pressure bulbs occur beneath the spread-type footing as estimated from the theoretical model by Boussinesq (1885) and numerical models (Aydan et al. 2016). It is interesting to note that compression and tension bulbs occur at the bottom of the socket-like foundation.

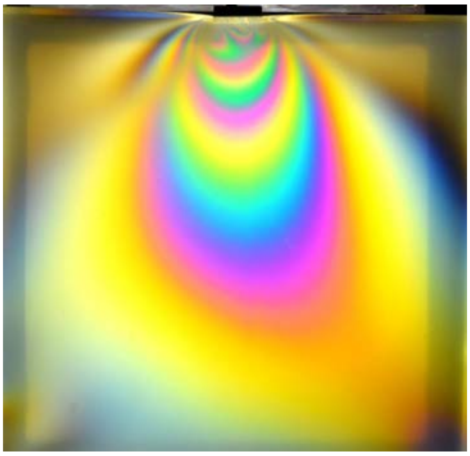


Figure 9. Stress distribution beneath spread-type foundation in continuum

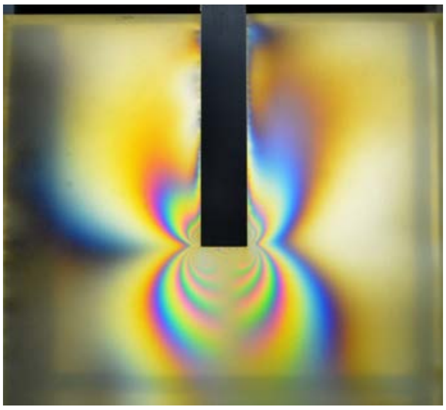


Figure 10. Stress distribution around socket-like foundation in continuum

Stress distributions in rock mass having discontinuities were studied by Gaziev and Erlikhman (1971), Maury (1969) and Hayashi (1966). It is shown that stress distributions may be quite different depending upon the inclination of rock discontinuities and their spacing. Figures 11 and 12 show stress distributions in layered and blocky rock mass models subjected to spread-type footing loading condition, respectively. It is interesting to note that the stress distributions may be entirely different from that of continuum models and some discontinuities in stress distributions at discontinuity planes take place.

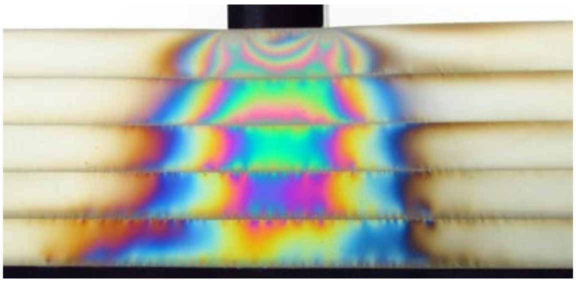


Figure 11. Stress distribution beneath spread-type footing in layered medium

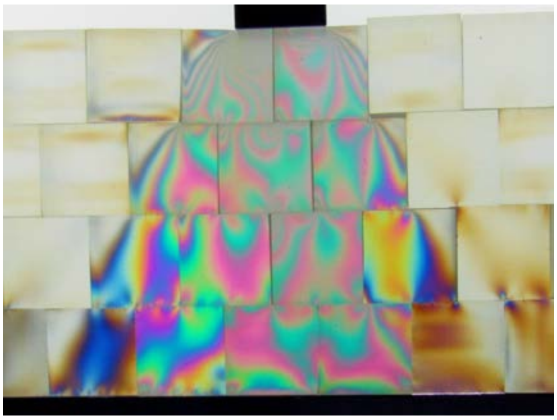


Figure 12. Stress distribution beneath spread-type footing in blocky medium

3.5 Cliffs and Slopes

The stability of slopes closely depend upon the orientation and spatial distribution of discontinuities in rock mass (Aydan et al. 1989; Aydan and Kawamoto 1992; Aydan 2015; Aydan et al. 2019) as well as the geometry of slopes and loading conditions. Figure 13 shows stress distributions in a valley subjected to high horizontal stresses. As noted from the distributions, very high stress concentrations occur at the bottom of the valley while the top part of experiences extensional straining.

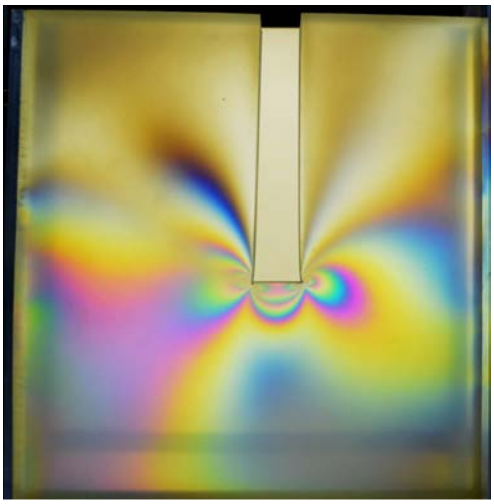


Figure 13. Stress distribution in a vertical valley subjected to high horizontal in-situ stress.

Figure 14 shows the stress changes during the failure process of cliffs made of gelatin (Horiuchi et al. 2019). As noted high stress concentration occur at the tip of the notch and tensile crack at the top part of the cliff. Once the crack starts to occur, the failure can not be prevented as pointed by Aydan and Kawamoto (1992) theoretically.

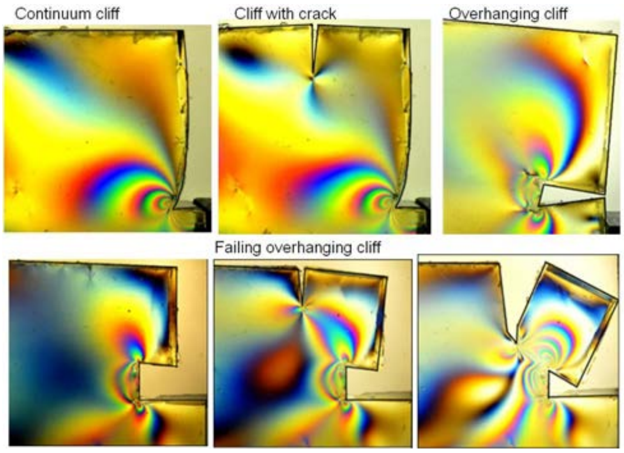


Figure 14. Stress distributions in failing cliffs (gelatin)

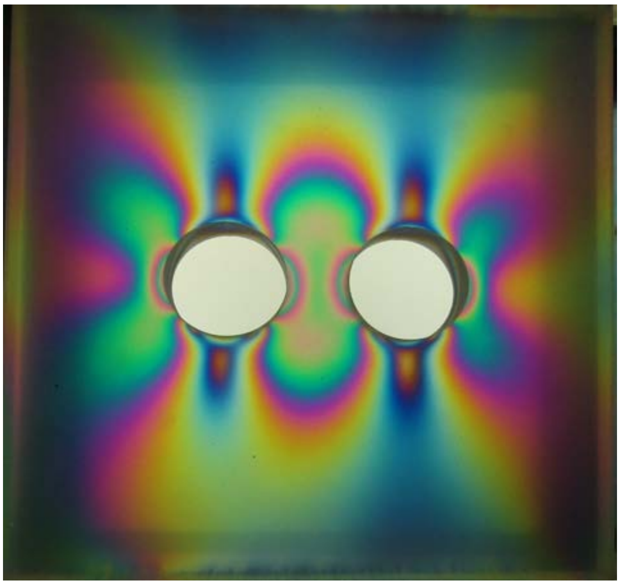


Figure 15. Stress distributions around double tunnel in continuum.

3.6 Underground Openings

The stability of underground structures is always an important field of research under different rockmass conditions and stress fields. Particularly, the stability of adjacent underground openings and width of the pillar between adjacent openings are of great importance for tunneling in urbanized areas. Figure 15 shows an example of stress distributions in the close vicinity of double-circular tunnels. As noted from the figure, stresses in the pillar section is larger than that at other parts. Figure 16 shows a long horizontal cavity subjected to high far field stresses in a continuum. In this tabular rock cavity stress concentrations are very high near the both ends of the underground opening. Similarly, Figure 17 shows the long horizontal shallow cavity subjected concentrated load on the ground surface. In this particular case, high stress concentrations occur at the end of the cavity and high tensile stresses in the roof of the cavity.

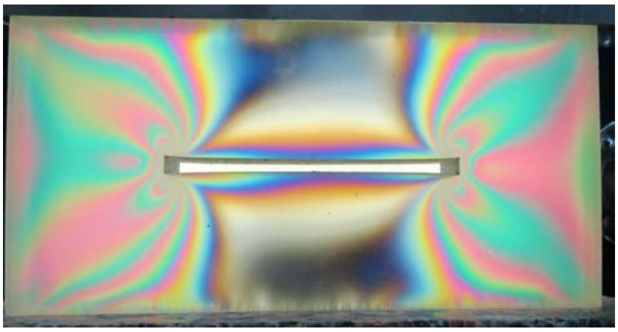


Figure 16. Stress distributions around tabular underground opening in continuum.

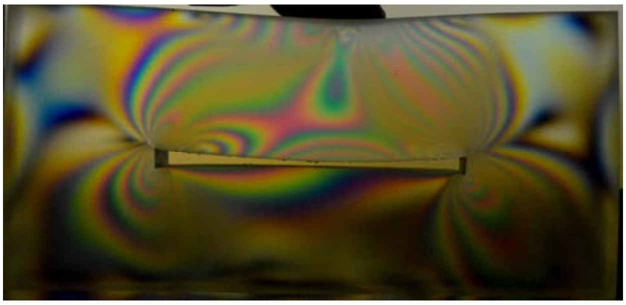


Figure 17. Stress distributions around tabular underground opening in continuum.

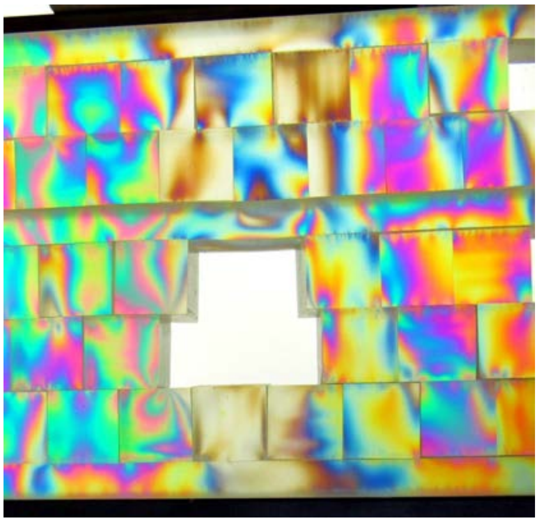


Figure 18. Stress distributions around underground opening in jointed complex rock mass

The existence of discontinuities is also of great importance for the stability of underground structures. Figure 18 shows the stress distributions in a rock mass models consisting of layers and blocks. As noted previously, the existence of discontinuities greatly alters the stress distributions and some discontinuities in stress field are observed at the joints and layer interfaces. Figure 19 shows a more complex rock mass situation in room and pillar mine model subjected to a concentrated load at the ground surface as well as the gravity load.

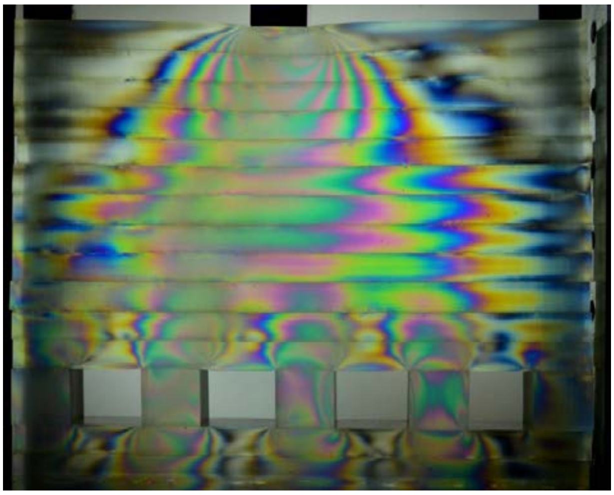


Figure 19. Stress distributions around room and pillar mine with surface load in discontinuum.

4. DISCUSSIONS AND CONCLUSIONS

Photo-elasticity technique was developed in the beginning of 18th century. It is the only technique to see the stress distributions by naked eyes. Despite the tremendous developments in computational techniques, it is still a viable technique to see the stress distributions in structures and understanding the basics of stress analyses as well as fracturing under static conditions. Furthermore, it is still one of the technique to evaluate stress conditions under dynamic conditions, which may be also used to check the computational results. It is also an efficient technique to understand stress distributions in discontinuous rock mass as well as stress distributions in the vicinity of earthquake faults. Besides the researches on various aspects of rock mechanics and rock engineering, the photo-elasticity technique is efficient technique to illustrate the basic mechanism of stress concentrations in structures for educational purposes. Therefore, it should be used as an educational tool for new-comers to the field of rock mechanics and rock engineering.

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