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Letter

Role of microscopic heterogeneity for deformability of rock mass from drilling

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Abstract: Heterogeneity of natural rock mass differs from most other engineering materials. Although the heterogeneity, such as macroscopic fracture, potentially contributes to the deformability of rock mass, evidence for macroscopic heterogeneity from field studies has been circumstantial. We present the results of field drilling energy experiment on the rock mass of tuff, limestone and marble types that shows the evidence for the rock mass deformability from macroscopic heterogeneity caused by fracture, reflecting borehole macroscopic heterogeneity associated with drill energy. The experimental results show that the macroscopic heterogeneity is expected to vary linearly with the fracture frequency, and depends on rock types and drilling energy. The contributions of macroscopic heterogeneity for deformability of rock mass have undergone a leading role.

Keywords: Macroscopic heterogeneity; Deformability; Fracture; Drilling energy

1. Introduction

Determination of the macroscopic heterogeneity of rocks is crucial for an understanding of rock mass deformability, because most behavior of rock mass is caused by the discontinuous nature of macroscopic fracture[1]. Prior studies using geological field data and borehole logs [1-9] revealed a marked decrease in deformation modulus, which can cause a large deformation raise and degradation of rock mass [10], with an increasing in fracture frequency and fracture spacing. However, a clear evidence for rock mass deformation formation from rock fracturing has been largely circumstantial until now. Here we present the results of in-situ drilling energy experiment on the rock mass of tuff, limestone and marble types that shows the evidence for the rock mass deformability from macroscopic heterogeneity caused by fracture, reflecting borehole macroscopic heterogeneity associated with drill energy. The experiments results show that the macroscopic heterogeneity is expected to vary linearly with the fracture frequency, and depend on rock types and drilling energy. When more fracture occurs on rock mass at seismic and huge engineering excavation, there is more macroscopic heterogeneity, so the ratio of deformation modulus is smaller. The contributions for deformability of rock mass, affected by the drilling energy, have undergone a leading role conversion from intact rock blocks to macroscopic heterogeneity.

Natural rocks are different from other engineering materials in that it contains discontinuous fracturing which render its structure macroscopic discontinuity and heterogeneity [7]. Large deformation, which can produce strong rock block motion and a fault slips, are associated with a remarkable increase in rock fracturing at seismic and huge engineering excavation [11]. Since laboratory experiments [12-16] have investigated the underlying deformation mechanisms of enhancement of fracturing on small jointed specimens, but it doesn't seem possible to predict accurately the deformability of rock masses due to the scaling rules in rock [17] and scale-dependent of fracture18, in situ tests provide direct information on deformability at very high cost and time consuming [8]. Also, simply treating the jointed rock as an equivalent continuum [11-22], all kinds of empirical correlations have been proposed for the determination of deformability based on rock quality designation (RQD) [8,23-26], rock mass rating (RMR) [1,25,27-30], Q-system (Q) [3,31], and geological strength index (GSI) [32-35]. Although various deformation mechanisms—such as joint density, joint orientation, joint spacing and broken pieces [23-35]—have been investigated, all of them seem to be triggered by macroscopic heterogeneity caused by fracturing.

Another question then arises: How to directly or indirectly measure the macroscopic heterogeneity for rock masses? It is known that the qualitative interpretation of the response of drill performance parameters to fracture provide enough detailed information [36]. However, it has not been possible to quantitatively investigate such a dependence of macroscopic heterogeneity. We have drawn an inspiration from standard deviation of local shear stress to quantitatively verify spatial heterogeneity [37]. From the drilling energy associated with rock properties, depending on the degree of correlation, its standard deviation of drilling energy extrapolates directly about homogeneous parts of the intact specimen [38]. Presumably, the spatial distribution property of drilling energy can also focus on the reflections on the macroscopic heterogeneity caused by fracturing. Although some drilling energy experiments using rock specimens have been conducted [39], the obtained results seem to not performance the correlation between the macroscopic heterogeneity and deformability.

Following this promising lead, we therefore present a systematic study of drilling energy to determine the influence of macroscopic heterogeneity on deformability within jointed rock mass. The most comprehensive experimental study of drill energy in situ states is that of ref.[40]. Two hundred and nineteen drill energy tests were conducted on the rock mass of different rock types using drill energy process monitoring apparatus, whose collection ability of 500 data per second are capable to accurately complete several hundred sets of drilling data storage. The rock mass in the Tsinling Mountains of China is associated with a variety of macroscopic fractures caused by seismic and huge excavation. Mainly containing gray marble, sandstone, tuff and crystalline limestone in the silurian period, the rocks contain fresh or slightly weathered and hard rock masses with good integrity, massive texture and thick layer. We repeated several experiments using the same rock types at the same conditions of in situ states.

2. Response of drill energy to rock fracturing

After each experiment, we found indications of response to drill energy on rock fracturing (Fig. 1). The drill energy from the 'a single fracture in marble' plotted against borehole depth in length range of f_2 are more scattered, since the presence of fracture pieces, than that in intact marble as shown in length range of f_1 and f_3 (Fig. 1a). Through one single fracture, a drop in the drill energy is in the void, followed by a rapid reduce, and come close to zero before returning to pre-fractured level as shown in length range of k_2 (Fig. 1b). On the other hand, the fracture and fracture zones are followed by the variability of drill energy where scattered effects can be observed in length range of k_3 and k_4 (Fig. 1b). The scatter effect of drill energy is associated with rock fracturing due to the heterogeneity of rock mass[38]. The fractures correspond to borehole heterogeneity (standard deviation) for different length ranges, respectively. A difference between the fracture and intact rock in the value of standard deviation for drill energy with the change along the borehole depth, the different value of standard deviation at increasing borehole depth is determined. Since the mechanical properties of fracture are only worse than those of the homogeneous parts in intact rock, the distribution properties of drill energy of the fracture parts are more scattered.

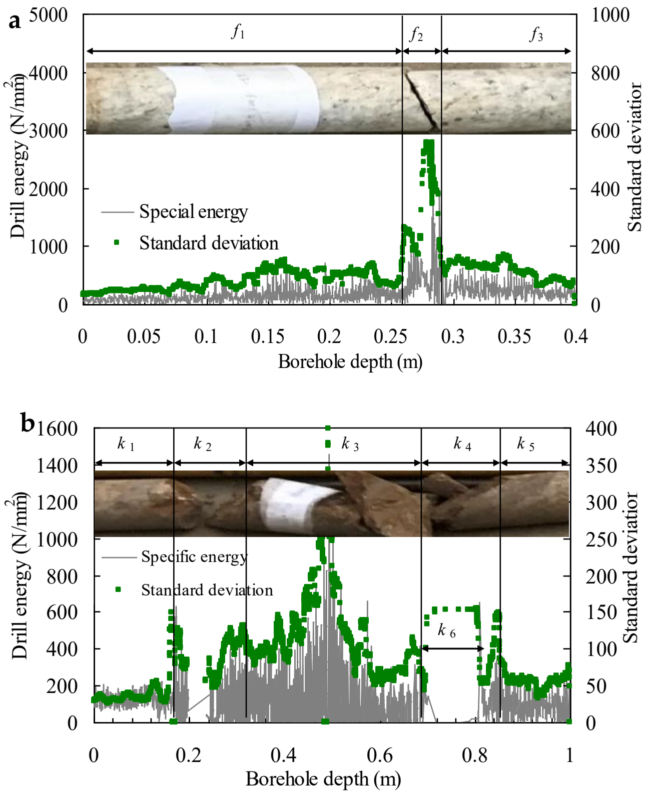

Fig. 1. The distributions of fracture, specific energy and standard deviation in each length range. **a**, The core log, drilling energy and standard deviation of drilling energy from the depths of 0 to 0.4 m in marble. Drilling energy and standard deviation correspond to a single fracture in marble was observed at the depth of 0.265~0.283 m. **b**, The core log, drilling energy and standard deviation of drilling energy from the depths of 0 to 1 m in limestone. Drilling energy and standard deviation correspond to fracture zones in limestone was observed at the depth of 0.0.185~0.831 m.

To directly investigate whether there is any fracture frequency effect on the macroscopic heterogeneity, we obtained 219 data of fracture frequency from each borehole logs after drilling energy test. Overall, fracture frequency [40] increased systematically with increasing borehole macroscopic heterogeneity (standard deviation of drill energy), which we term 'standard deviation' for simplicity hereafter in macroscopic heterogeneity of sandstone, limestone and granite (Fig. 2), showing that a larger fracture frequency corresponds to a larger value of standard deviation for different rock types. On the other hand, with increased fracture frequency, the standard deviation increases linearly and monotonically, and only depends on rock types (sandstone, limestone and granite) and drilling energy (397.4, 292.2 and 108.3 N/mm²). Hence, the fracture frequency using standard deviation can be estimated as

$$\lambda = \xi s \tag{1}$$

where λ is fracture frequency, s is the standard deviation of drill energy, ζ is the linear fitting parameter for the $\lambda \sim s$ curve.

The modulus ratio a is the ratio of the deformation modulus of rock mass E_m to the deformation modulus of intact rock E_r (measured by laboratory tests) for deformation processes, defined as $a=E_m/E_r$ [24], and can be obtained from the function $E_m=y(E_r)$ [42]. In situ modulus of deformation tests of three rock types demonstrates a systematic reduction of the modulus ratio E_m/E_r with increasing borehole macroscopic heterogeneity (standard deviation) (Fig.3). We find a similar dependence for a of the three rocks on fracture frequency, with systematically lower value of a toward larger fracture frequency, but it is immune to rock types (Fig. 3a). If we compare our data for the three rock types with a a~λ model (a~$f(\lambda)$ model obtained from $a=h(RQD)$ model [7,8] and $RQD=g(\lambda)$ model [40] describing the behavior of rock mass, it becomes clear that the a measured on each of the three rock mass is more strongly fracturing dependent at the higher fracture frequency (about >2) than in the a~λ model (Fig. 3 a). However, the a is higher at low drill energy for the granite (397.4 N/mm²) than that at high drill energy for limestone (292.2 N/mm²) and sandstone specimen (108.3 N/mm²), possibly reflecting rock deformability associated with drill energy (fig. 3b). Our observations of the progressive decrease in deformation modulus with standard deviation, from low drill energy to high drill energy, provides the first convincing in situ experiment evidence for the rock mass deformation from heterogeneity of macroscopic fracture. The decreased a value of the three rock masses as compared to the modified a~λ model for the behavior of fracturing mechanics for rock mass suggest that macroscopic heterogeneity introduced during fracture are responsible for the substantial deterioration of the deformation modulus for rock mass.

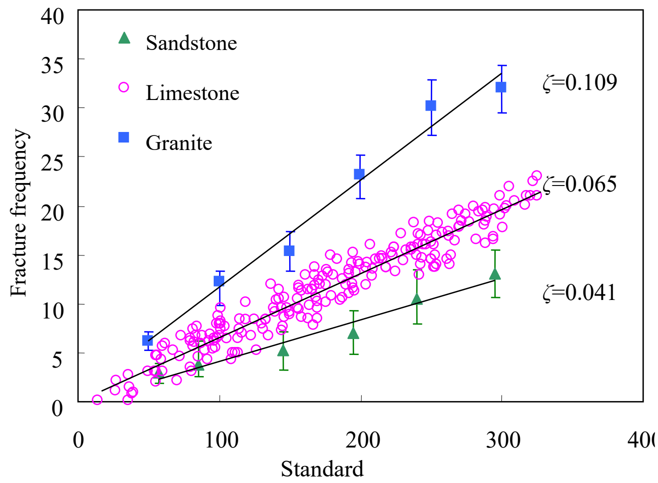

Fig. 2. Relationship between fracture frequency and standard deviation of drill energy.

3. Deformability of Rock Mass from Drilling Project

From the experiment results in Fig. 2, we assume that the ratio of the fracture frequency λ to standard deviation s (macroscopic heterogeneity) is constant, the a~λ model can be modified as:

$$a = \frac{E_m}{E_r} = 10^{\frac{\eta g(\xi s)}{100} - \eta} \tag{2}$$

where E_m is deformation modulus of rock mass; E_r is deformation modulus of intact rock; $g(x)$ is $RQD=g(x)$ function [40]; s is the standard deviation of drill energy, reflect borehole macroscopic heterogeneity; ζ is the linear fitting parameter for the λ-s curve; η is a parameter related to e, ζ and E_r, $\eta = e\zeta / E_r$. The value of η in agreement with the η' value obtained from the modified model ($\eta' = 1001ga/[g(\zeta s)\text{-}100]$) (Fig. 3b, inset). For the value of ζ of 0.041, 0.065 and 0.109, we obtain the results of the modified model, describing the deformation behavior of macroscopic heterogeneity for the three rocks (Fig. 3b), to provide a prediction for rock mass deformability at seismic and huge engineering excavation.

We used the modified a~λ model to assess the contributions of macroscopic heterogeneity for deformability of rock mass. This model, evaluated at the standard deviation of 65 to150 for the three rocks and at the deformation modulus (drilling energy) of 22.6 (397.4), 9.7 (292.2) and 2.3 GPa (108.3 N/mm²), yields values of a between 0.878 and 0.119. Such deformability is larger due to macroscopic fracture rather than intact rock block. For the tested rock mass of sandstone, limestone and granite types, comparable levels of deformability would be expected from macroscopic heterogeneity alone for the standard deviation of 0 to +∞. The granite rock mass with a population of fracture in the case of the same standard deviation, duo to a higher deformation modulus, displayed much higher levels of a than sandstone and limestone of comparable macroscopic heterogeneity. Moreover, in the case of complete macroscopic homogeneity (no fractures, standard deviation tend to zero, and the a value close to 1), the contribution of intact rock blocks is major prominent for deformability of rock mass. In the case of standard deviation tend to +∞ (the a value close to 1), the contributions of macroscopic heterogeneity play a leading role in the deformability. We conclude therefore that deformability of rock mass associated with macroscopic heterogeneity caused by fracturing (standard deviation 0 to +∞) may contribute comparably with rock blocks their own deformability, especially in regions of broken rock that are subject to relatively high level of fracture and consequently high macroscopic heterogeneity, and for intact blocks motion along fracture surface that provide high level of fault slips for deformation of rock mass [42]. The contributions for deformability of rock mass, affected by the drilling energy, have undergone a leading role conversion from intact rock blocks to macroscopic heterogeneity caused by fracturing at seismic and huge engineering excavation.

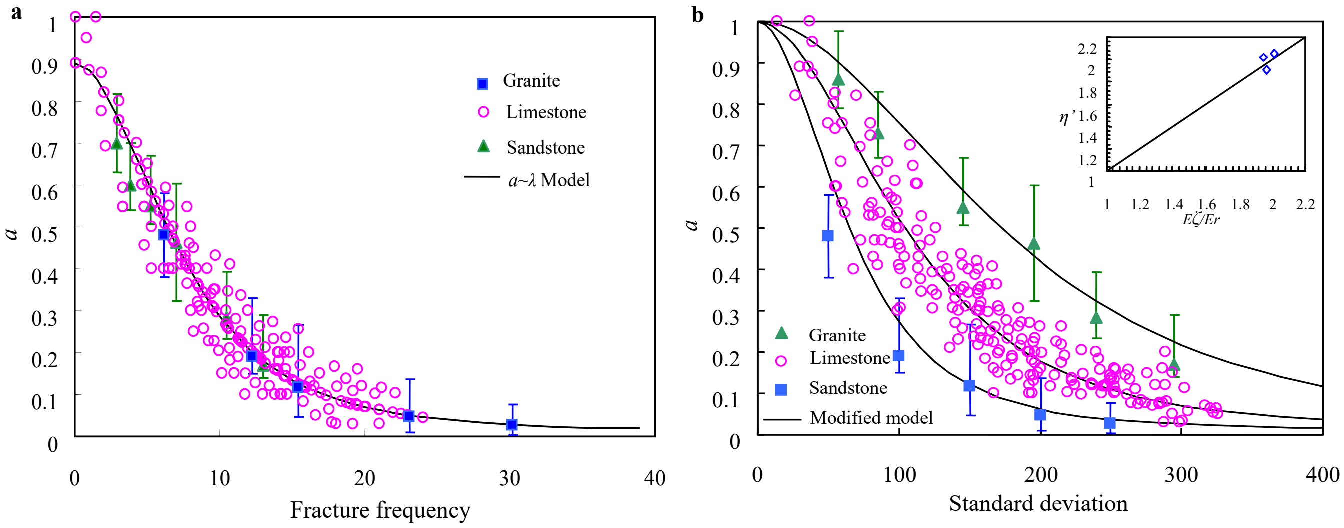

Fig. 3. The ratio of deformation modules to the deformability summation of rock block and fracture slips as a function of the fracture frequency and macroscopic heterogeneity (standard deviation of drill energy). **a**, The experiment results show that a dependence for *a* of the three rocks on fracture frequency, with systematically lower value of *a* toward larger fracture frequency, but it is immune to rock types. The *a* measured on each of the three rock mass is more strongly fracturing dependent at the higher fracture frequency than in the *a*~*λ* model. **b**, The experiment results show that the *a* is higher at low drill energy for the granite (397.4 N/mm^2) than that at high drill energy for limestone (292.2 N/mm^2) and sandstone specimen (108.3 N/mm^2), possibly reflecting deformability associated with drill energy. The experiment data follows the modified *a*~*λ* model, where the value of η,$\eta = e\zeta/E_r$, is in agreement with the η' ($\eta' = 1001ga/[g(\zeta s)\text{-}100]$) value obtained from the modified model.

4. Conclusions

Our data demonstrate that the ratio of deformation modulus associated with macroscopic heterogeneity from fracturing is affected by the drilling energy of rock. The macroscopic heterogeneity is expected to vary linearly with the fracture frequency, and depend on rock types and drilling energy. When more fracture occurs on rock mass at seismic and huge engineering excavation, there is more macroscopic heterogeneity, so the ratio of deformation modulus is smaller.

Author contributions

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Conflicts of Interest

All the authors claim that the manuscript is completely original. The authors also declare no conflict of interest.

Data availability

All relevant data related to this manuscript are available and can be provided upon reasonable request.

References

1. Bieniawski ZT. Determining rock mass deformability: experience from case histories. Int J Rock Mech Min Sci & Geomech Abstr. 1978; 15: 237-247.
2. Nicholson GA, Bieniawski ZT. A nonlinear deformation modulus based on rock mass classification. Int J Min Geol Eng. 1990; 8: 181-202.
3. Barton N. Some new Q-value correlations to assist in site characterization and tunnel design. Int J Rock Mech Min Sci. 2002; 39: 185-216.
4. Hoek E, Diederichs MS. Empirical estimation of rock mass modulus. Int J Rock Mech Min Sci. 2006; 43: 203-215.
5. Gokceoglu C., et al., Predicting the deformation moduli of rock masses. Int J Rock Mech Min Sci. 2003; 40: 701-710.
6. Sonmez H., et al., Estimation of rock modulus: for intact rocks with an artificial neural network and for rock masses with a new empirical equation. Int J Rock Mech Min Sci. 2006; 43: 224-235.
7. Zhang LY. Determination and applications of rock quality designation (RQD). J Rock Mech Geotech Eng. 2016; 8: 389-397.
8. Zhang LY. Einstein, H. H., Using RQD to estimate the deformation modulus of rock masses. Int J Rock Mech Min Sci. 2004; 41: 337-341.
9. Hashemi M., et al., Application of rock mass characterization for determining the mechanical properties of rock mass: a comparative study. Rock Mech Rock Eng. 2010; 43: 305-320.
10. Sagong M., et al., Experimental and numerical analyses of an opening in a jointed rock mass under biaxial compression. Int J Rock Mech Min Sci. 2011; 48: 1055-1067.
11. Palmstrom A, Singh R. the deformation modulus of rock massed-comparisons between in situ tests and indirect estimates. Tunn. undergr sp tech. 2001; 16: 115-131.
12. Kilburn C. Precursory deformation and fracture before brittle rock failure and potential applica- tion to volcanic unrest. J Geophys Res-Sol Ea. 2012; 2: B02211.
13. Li Y., et al., Experimental and numerical investigations on the shear behavior of a jointed rock mass. Geosci J. 2016; 20: 371-379.
14. Singh M., et al., Strength and deformational behaviour of a jointed rock mass. Rock Mech Rock Eng. 2002; 35: 45-64.
15. Tang CA., et al., Numerical studies of the influence of microstructure on rock failure in uniaxial compression-Part I: Effect of heterogeneity. Int J Rock Mech Min Sci. 2000; 37: 555-569.
16. Sagong M., et al., Experimental and numerical analyses of an opening in a jointed rock mass under biaxial compression. Int J Rock Mech Min Sci. 2011; 48: 1055-1067.
17. Allegre CJ, Le mouel JL, Provost A. Scaling rules in rock fracture and possible implications for earthquake prediction. Nature. 1982; 297: 47-49.
18. Renshaw CE, Park JC. Effect of mechanical interactions on the scaling of fracture length and aperture. Nature. 1997; 386: 482-484.
19. Brady BHG, Brown ET. Rock mechanics for underground mining. (London, UK: George Allen and Unwin, 1985).
20. Brown ET. The nature and fundamentals of rock engineering. (Oxford, UK: Pergamon Press, 1993).
21. Hoek E, Kaiser PK, Bawden WF. Support of underground excavations in hard rock. (Rotterdam: A.A. Balkema; 1995).
22. Zhang LY. Engineering properties of rocks. (Amsterdam: Elsevier Ltd., 2005).
23. Deere DU, Hendron AJ, Patton FD, Cording EJ. Design of surface and near surface construction in rock. (New York: American Institute of Mining, Metallurgical and Petroleum Engineers, 1967).
24. Coon RF, Merritt AH. Predicting in situ modulus of deformation using rock quality indexes. (ASTM International; 1970).
25. Serafim JL, Pereira JP, Consideration of the geomechanical classification of Bieniawski. (Rotterdam: A.A. Balkema, 1983).
26. Zhang LY. Estimating the strength of jointed rock masses. Rock Mech Rock Eng. 2010; 43: 391-402.

27. Yudhbir WL, Prinzl F. An empirical failure criterion for rock masses. (Melbourne, 1983).
28. Mitri HS, Edrissi R, Henning J. Finite element modeling of cablebolted stopes in hard rock ground mines.(Albuquerque, USA. 1994).
29. Sheorey PR. Empirical rock failure criteria. (Rotterdam: A.A. Balkema, 1997).
30. Aydan Ö, Dalgic S. Prediction of deformation behavior of 3-lanes Bolu tunnels through squeezing rocks of North Anatolian fault zone (NAFZ). (Taipei, China; 1998).
31. Barton N, Loset F, Lien R, Lunde J. Application of Q-system in design decisions concerning dimensions and appropriate support for underground installations. Proceedings of the International Symposium, Pergamon Press, 1980; 2: 553-561.
32. Hoek E, Brown ET. Practical estimates of rock mass strength. Int J Rock Mech Min Sci. 1997; 34: 1165-1186.
33. Hoek E. Personal communication. (Rocscience; 2004).
34. Gokceoglu C, Sonmez H, Kayabasi A Predicting the deformation moduli of rock masses. Int J Rock Mech Min Sci. 2003; 40: 701-710.
35. Hoek E, Diederichs MS. Empirical estimation of rock mass modulus. Int J Rock Mech Min Sci. 2006; 43: 203-215.
36. Schunnesson H. RQD predictions based on drill performance parameters. Tunn Underg Sp Tech. 1996; 11: 345-351.
37. Yamashita F, Fukuyama E, Kazuo M, Takizawa S, Xu S, Kawakata H. Scale dependence of rock friction at high work rate. Nature. 2015; 528: 254-257.
38. Teale R. The concept of specific energy in rock drilling. Int J Rock Mech Min Sci. 1965; 2: 57-73.
39. Thomas R., et al. Rock strength determination from scratch tests. Eng Geol. 2012; 147-148: 91-100.
40. Priest SD, Hudson J. Discontinuity spacing in rock. Int J Rock Mech Min Sci & Geomech Abstr. 1976; 13: 135-148.
41. C Li. A Method for Graphically Presenting the Deformation Modulus of Jointed Rock Masses. Rock Mech Rock Eng. 2001; 34: 67-75.
42. Ma KF., et al. Slip zone and energetics of a large earthquake from the Taiwan Chelungpu-fault drilling project. Nature. 2006; 444: 473-476.