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Investigation of the hydraulic properties of deep fractured rocks around underground excavations using high-pressure injection tests

Zhen Huang[a,b,c,*], Xiaozhao Li[a], Shijie Li[b], Kui Zhao[b], Rui Zhang[d]

[a] School of Earth Sciences and Engineering, Nanjing University, Nanjing 210023, China
[b] School of Resources and Environment Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China
[c] State Key Laboratory for GeoMechanics & Deep Underground Engineering, China University of Mining and Technology, Xuzhou 221116, China
[d] Kunming Survey, Design and Research Institute CO. LTD of Creec, Kunming 650200, China

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ABSTRACT

Groundwater inrush during excavation is one of the greatest challenges in modern underground engineering. The characteristics of groundwater inrush induced by high-pressure water in fractured rocks are poorly understood, and the risk assessment of water inrush hazard associated with deep geological conditions remains to be improved. Here, we present an in situ high-pressure fluid injection experimental investigation of the hydraulic properties of deep natural fractured rocks. We observe that the injection rate increases as a nonlinear function of the injection pressure, and the process can be divided into an initial flow phase and a flow mutation phase, which indicates flow regime variations during fluid injection. Fluid injection primarily triggers fracture dilation and then results in an evident increase in rock permeability. A conceptual model involving multiple physical processes is derived to describe the permeability evolution and flow behavior of fractured rocks throughout the high-pressure fluid injection tests. The results provide valuable insight for evaluating the evolution of the hydraulic properties of the surrounding rocks in relation to water inrush and dewatering designs.

1. Introduction

Underground space development and utilization ranging from tunnel construction to coal production and other infrastructure (Huang et al., 2016a) are frequently associated with groundwater inrush accidents (Ma et al., 2017), which present one of the greatest challenges in underground engineering (Bukowski, 2011; Farhadian et al., 2016; Wang et al., 2017). In deep engineering, the risk of water inrush increases under high groundwater pressures and deeply deposited environments (Chen et al., 2015a). The natural surrounding rocks play an important role to prevent water inrush. Therefore, the hydraulic properties of natural surrounding rocks are of great importance for understanding groundwater flow and investigating the risk of water inrush.

Investigations on the hydraulic properties such as permeability and the flow behaviors underlying fluid overpressure have drawn increasing attention from various research areas. Laboratory penetration tests (e.g., Wang and Park, 2002; Okazaki et al., 2014), physical model tests (e.g., Wang et al., 2008; Liang et al., 2016; Ma et al., 2017), numerical analyses (e.g., Figueiredo et al., 2015; Pardoen et al., 2016) and in situ hydraulic tests (e.g., Angulo et al., 2011; Derode et al., 2013; Huang et al., 2014; Chen et al., 2015a, 2015b; Huang et al., 2016a, 2016b) have been implemented to characterize the evolution of the hydraulic properties of natural geomaterials. Compared with the previous methods, in situ hydraulic tests are commonly used as reliable methods for investigating the hydraulic properties of fractured rocks in field situations (Neuman, 2005; Hamm et al., 2007; Chen et al., 2015a, 2015b; Huang et al., 2016a, 2016b). Most in situ tests currently in use are conventional hydraulic tests (Neuman, 2005; Audouin and Bodin, 2007; Hamm et al., 2007; Angulo et al., 2011; Quinn et al., 2011, 2013), which typically perform at adequately low injection pressures or injection rates that fluid flow in the test interval is considered Darcy flow (Quinn et al., 2011; Chen et al., 2015a, 2015b). But, the hydraulic properties under high water pressures and in deeply buried environments are much more complicated than those under shallow conditions and low water pressures (Zhou et al., 2018), involving complex and heterogeneous mechanical properties and hydraulic diffusivity (Derode et al., 2013). The conventional hydraulic tests are inappropriate for such deep circumstances. This restriction can favorably be addressed by enhanced high-pressure injection tests, in which a large volume of fluid is injected into the rocks, commonly through a single borehole (Rutqvist et al., 1998; Chen et al., 2015a, 2015b). This technique has

* Corresponding authors at: School of Earth Sciences and Engineering, Nanjing University, Nanjing, Jiangsu 210023, China.
E-mail address: zhenhuang89@126.com (Z. Huang).

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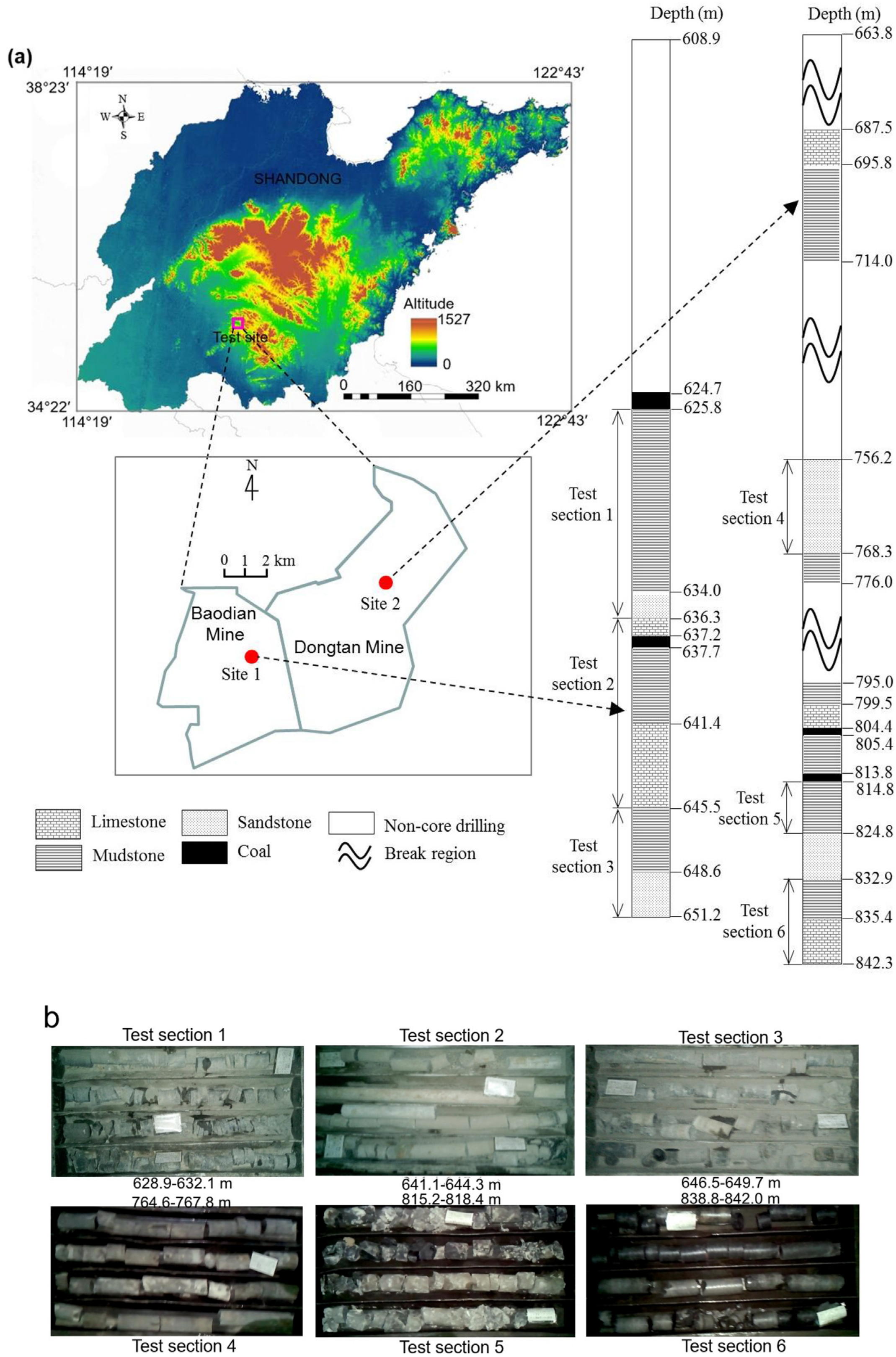

Fig. 1. (a) Location of the study area and stratigraphic columns of the injection boreholes. (b) Photographs of partial rock cores of the test sections (after Huang et al., 2016a). The six test sections are located at depths of 625.8–636.3 m, 636.3–645.5 m, 645.5–651.2 m, 756.2–768.3 m, 814.8–824.8 m and 832.9–842.3 m below the ground surface, respectively.