Engineering Geology 234 (2018) 112–121

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Interpretation of high pressure pack tests for design of impervious barriers under high-head conditions

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ARTICLE INFO

Keywords:
High pressure packer test
Permeability
Impervious barrier
High dam foundation

ABSTRACT

High pressure packer test (HPPT) is an enhanced constant head packer test widely applied for characterizing the permeability or coupled hydromechanical properties of fractured rocks under high water pressure condition, but it remains an issue about how to choose a representative quantity from the test data for the design of impervious barriers in high-head geotechnical projects. In this study, the typical type curves of HPPTs are summarized and related to the intactness of rocks, flow condition in fractures and the possible hydraulic fracturing phenomenon in the tested rocks. Based on an interpretative model recently developed for HPPTs, a criterion is proposed to determine a proper permeability rate from the HPPT data for design of grout curtains by taking into account the type curves and the transition of flow conditions, and is applied to illustrate the implication of the proposed criterion for the design of impervious barrier in a high arch dam foundation. The proposed criterion could be of significance in the design of impervious barriers for reducing the risk of leakage in rocks under high water pressure condition.

1. Introduction

Over the last two decades, a considerable number of 200 – 300 m high dams and 400 – 800 m high-head pumped-storage power stations have been constructed or under construction in the world, with at least half of them in China, as shown in Fig. 1. During operation, the water pressure in the foundation rocks of dams and the surrounding rocks of concrete-lined tunnels upstream the grout curtains may be as high as 2 – 8 MPa, and the hydraulic gradient in the rocks between the grout curtains and the drains may reach a magnitude over 20 – 30, as depicted in Fig. 2. The high water pressure and hydraulic gradient pose a great challenge to the control of seepage in the foundation rocks of high dams and the surrounding rocks of high pressure tunnels, as evidenced by the leakage events frequently occurring in the dam foundations during the impounding of reservoirs and around the tunnel systems during the early operation period of pumped-storage power stations (e.g. Malkawi and Al-Sheriadeh, 2000; Turkmen, 2003; Zhou et al., 2015; Chen et al., 2016a, 2016b). Catastrophic accidents may even be caused, when the pressure significantly reduces the effective normal stress in structural planes or induces hydraulic fracturing in rocks. A well-known example is the collapse of the Malpasset dam occurred in December 2, 1959, shortly before the first filling of the reservoir was completed. This accident was commonly attributed to the development of high uplift pressure (Londe, 1985) or both high uplift pressure and high seepage pressure (i.e. high hydraulic gradient) deep in the foundation rock (Wittke, 1990).

The constant pressure packer test (CPPT) is also known as constant head test, packer test, pressure test or Lugeon test in various engineering fields (e.g. hydrogeology, civil engineering and petroleum engineering). It has been an important tool to characterize the intactness, groutability and/or permeability of rocks around a borehole (Lugeon, 1933; Louis and Maini, 1970; Lancaster-Jones, 1975; Houlsby, 1976; Price et al., 1977; Brassington and Walthall, 1985; Mollah and Sayed, 1995; Zhan et al., 2016). This test conventionally applies with P_{max} = 1 MPa in Europe and China or 1 psi per foot of overburden in USA, where P_{max} is the maximum injection pressure. The test is commonly interpreted with Lugeon value or secondary permeability index for characterizing the intactness and groutability of rocks (Lancaster-Jones, 1975; Houlsby, 1976; Brassington and Walthall, 1985; Foyo et al., 2005). The hydraulic conductivity or transmissivity of the tested rocks or fractures can also be calculated by applying the Darcy's law-based methods (e.g. Thiem, 1906; Hvorslev, 1951; Zangar, 1953; Gibson, 1963) or the cubic law for laminar flow in fractures (Bear, 1972; Witherspoon et al., 1980; Zimmerman and Bodvarsson, 1996).

With the increase of water pressure and hydraulic gradient, however, the flow in rocks may deviate remarkably from linearity due to

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https://doi.org/10.1016/j.enggeo.2018.01.006
Received 1 April 2017; Received in revised form 4 January 2018; Accepted 6 January 2018
Available online 09 January 2018

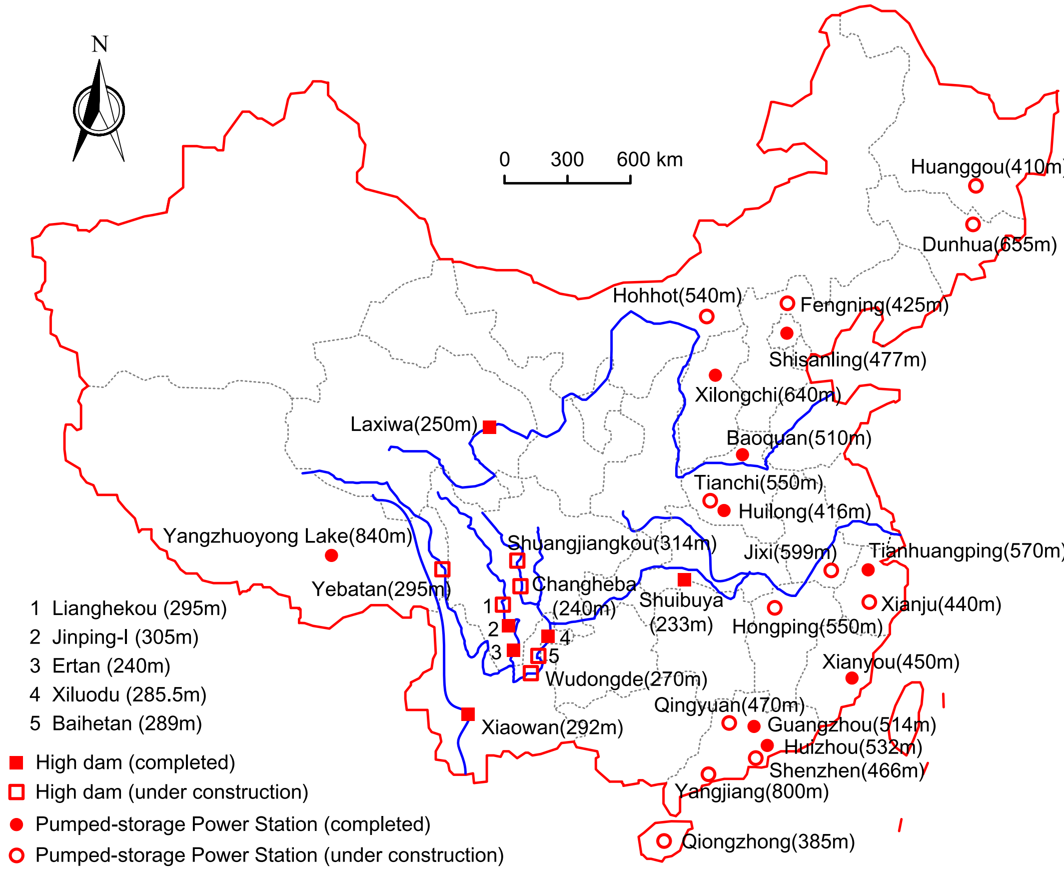

Fig. 1. Part of high dams and high-head pumped-storage power stations constructed or under construction in China.

high flow velocities in fractures (Louis, 1969; Zimmerman and Bodvarsson, 1996). Hydraulic fracturing may even be induced under high water pressure (Doe and Geier, 1990; Rutqvist et al., 1998). As an enhanced constant pressure packer test, therefore, high-pressure packer test (HPPT) is often performed to investigate the flow behaviors and the hydrofracturing risks in the rock formations under high water pressure and deeply buried environment (Londe and Sabarly, 1966; Doe and Geier, 1990; Cornet and Morin, 1997; Rutqvist et al., 1998; Cornet et al., 2003; Evans et al., 2005; Cappa et al., 2006; Derode et al., 2013; Huang et al., 2014; Chen et al., 2015a). The HPPT is commonly conducted in a single borehole, but differs from the conventional CPPT in that water is injected into the rocks with a magnitude of P_{max} much higher than 1 MPa and the flow in the tested rocks or fractures is prone to become non-Darcian (Derode et al., 2013; Klepikova et al., 2013).

The types of typical $P-Q$ curves for packer tests and their correlations to the rock conditions have been well understood (e.g. Houlsby, 1976; Royle, 2002; Foyo et al., 2005), and the curves are more likely to become nonlinear for HPPTs under higher injection pressures (e.g. Rutqvist et al., 1998; Chen et al., 2015a). The Darcy's law-based methods are still widely used to calculate the permeability for their ease of implementation and computational efficiency (Cornet and Morin, 1997; Rutqvist et al., 1998; Evans et al., 2005; Hamm et al., 2007; Angulo et al., 2011; Huang et al., 2014; Lo et al., 2014), where the non-Darcy nature of fluid flow in fractured rocks at high flow rates or hydraulic gradients is disregarded and the permeability of the test rocks can be underestimated by as much as one order of magnitude (Elsworth and Doe, 1986). A considerable number of Forchheimer's (1901) law or Izbash's (1931) law-based interpretative models (e.g. Choi et al., 1997; Wu, 2002; Wen et al., 2006; Mathias et al., 2008; Moutsopoulos, 2009; Eck et al., 2012; Mijic et al., 2013) are available, but with only a few of them targeted or suited for HPPTs (e.g. Yamada et al., 2005; Quinn et al., 2011; Chen et al., 2015b).

However, when the HPPTs are performed for ground treatment and impervious barrier design in civil engineering under high-head conditions, it remains an issue about how to choose a representative quantity from the HPPT data with consideration of both nonlinear flow behavior and hydrofracturing. Liu et al. (1996) suggested to adopt the Lugeon value at the operating pressure for the design of an impervious system, but this treatment may dramatically increase the leakage risk of the design due to the nonlinearity of flow in the vicinity of the borehole. In this study, the types of $P-Q$ curves obtained from HPPTs available in the literature are summarized. A criterion is then proposed for determining the representative Lugeon values of rock formations from the $P-Q$ curves, based on the Forchheimer's law-based analytical model for HPPTs developed by Chen et al. (2015b). A case study is finally presented to show the implications of the proposed criterion for the design of grout curtain in a high arch dam foundation in southwestern China.

2. HPPTs and their $P-Q$ curves

2.1. Equipment and test procedure for HPPTs

Quite a number of testing systems are available for HPPTs and hydraulic fracturing, with some of them equipped with three pressure sensors between, above and below the packers, respectively (e.g. Quinn et al., 2016). The equipment adopted in this study consists of a downhole component for conducting the injection and an above-ground component for monitoring the procedure and recording the data, as shown in Fig. 3. The piston pump and the pipe system are enabled to operate in much higher pressure (depending on the operating pressure of hydraulic structures) over a wider range of flow rates, and the inflatable packers are made long enough (typically over 80 cm) to reliably isolate the test sections (commonly between 1 and 10 m in length) from