Tunnelling and Underground Space Technology 40 (2014) 1–15

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Control of rock jacking considering spread of grout and grouting pressure

Jalaleddin Yaghoobi Rafi *, Håkan Stille

Royal Institute of Technology, Brinellv. 32, SE-100 44 Stockholm, Sweden

ARTICLE INFO

Article history:
Received 17 November 2012
Received in revised form 8 August 2013
Accepted 19 September 2013
Available online 15 October 2013

Keywords:
Grouting pressure
Jacking
Penetration length
Grout take

ABSTRACT

This paper describes a theoretical approach for monitoring fracture dilatancy (or "jacking") during grouting. From this, a methodology to optimize the grout pumping pressure has been developed, based on the required penetration length (i.e. the distance that the grout spreads from the grout hole into the network of fractures within the rock mass). Empirical rules are put forward to prevent the damage that may result from uncontrolled deformation (Jacking) of the fractures, by limiting either pumping pressure or the injected grout volume, or by a combination of both. The state of the fractures and the spread of the grout when these limits are reached are discussed. The theoretical approach, which is referred to here as the Real Time Grouting Control Method, enables the estimation of grout penetration length or "spread" in real time. This gives an opportunity to monitor fracture dilation as it happens and, for the purpose of this paper, the allowable limits of elastic deformation and jacking have been estimated based on the grout spread. Two case histories are analyzed, for which the physical reaction of the fracture deformation with time and grout spread are determined from the recorded pressure and flow. By comparing the observed physical reaction with the theories for jacking presented here, the Real Time Grouting Control Method has been validated, and it is shown that this theoretical approach is superior to commonly used empirical methods, in that it allows the optimization of the pumping pressure to achieve a given penetration length in the shortest time and with an acceptable fracture dilatancy. This approach is a major step forward in customizing grouting works.

1. Introduction

Many factors affect the grouting of a fractured rock mass, for example the grout mixture properties, the pumping pressure, and the geological properties of the rock mass. The selection of the grouting pressure is one of the key factors that affect the grouting process directly. For example if a low pressure is chosen, the grout may not penetrate into the network of natural fractures within the rock mass while high pressure may cause some of fractures to dilate, so that the spread of the grout is uncontrolled and permanent deformation of rock mass occur. Such deformations may have negative effects on sensitive surface structures, and also on the effectiveness of the grouting. Up until today, indirect and substituting measures have been used to check whether the grouting has fulfilled its objective, which is to fill existing fractures with the lowest amount of grout and in the shortest time without causing any damage. With such methods, the risk of excess pressure and the excessive spread of grout in the fractures are controlled by limiting the maximum pressure and the maximum volume of grout to be pumped.

As a practical solution to avoid unwanted deformations, Houlsby (1990) suggested that the maximum allowable pressure should be based on the depth of the fractures and the rock conditions. Similar recommendations can be found in many text-books (see for example Weaver, 1991). See Fig. 1. With this approach, the main limitation is the uncertainty about the state of the fractures after grouting, i.e. whether or not the ground has been disturbed or new fractures have been induced, and also whether the grout spread has been satisfactory. Frequently, the initial decisions on grout mixture and borehole spacing are imprecise, so that the use of engineering experience and judgment is an important factor.

Lombardi and Deere (1993) recognized that the rock becomes "tighter" in successive phases of grouting, i.e. at least partial filling of at least some of the fractures occurs so that the rock mass permeability will be reduced. Consequently, they introduced the procedure of using a progressively lower volume of grout at a progressively higher pressure to grout the finer fissures. They proposed that, when grouting in this manner, the product of grout pressure and volume should not exceed the given value at the design stage, which they called the Grouting Intensity Number (GIN). This method has been used in many projects, despite some ambiguities and limitations. Since there is no mechanically based theory for choosing the GIN value, the applicability of this method has been questioned (Ewert, 1996; Rombough et al., 2006; Shuttle et al., 2007).

* Corresponding author. Tel.: +46 (0)8 790 8675.
E-mail addresses: jyr@kth.se (J.Y. Rafi), hakan.stille@byv.kth.se (H. Stille).

0886-7798/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tust.2013.09.005

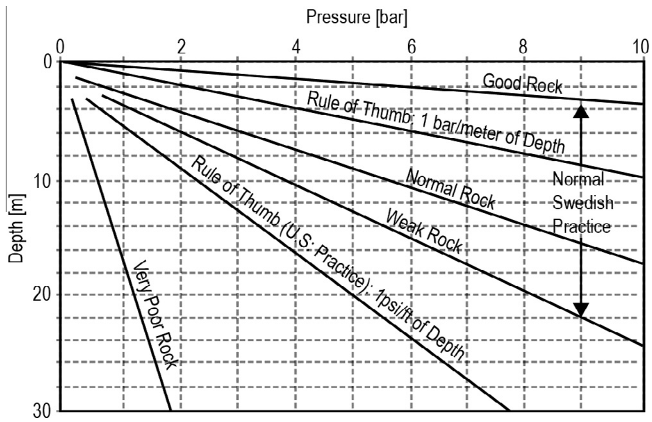

Fig. 1. Grouting pressure according to practice in Sweden and the USA (Weaver, 1991). Both rock quality and depth of grouting are important factors in determining grouting pressure.

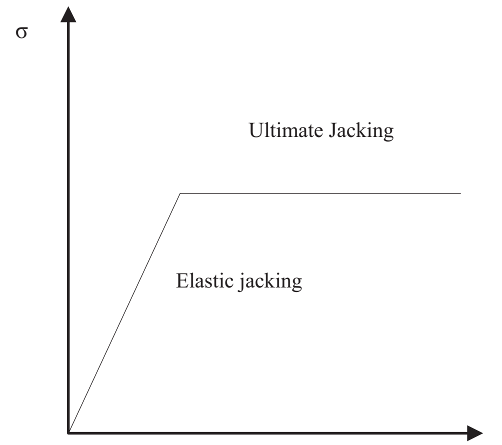

Fig. 3. In the elastic zone, deformation of the fracture may be compensated during unloading. Increasing the stresses causes permanent deformation (ultimate jacking).

Aperture Controlled Grouting is another method which can be used. According to Carter et al. (2012) once the volume of grout to be pumped has been decided from the estimated volume of the void to be filled and the chosen hole spacing, grout rheology should be adjusted to match the fracture characteristics, so that the pressure builds to refusal at the required take. Bonin et al. (2012) proposed a decision chart for defining the sequence of thickening the grout mixture. Using a televiewer to produce high-resolution images of fractures to be grouted (Ivanetich et al., 2012), and simulating the geological condition through discrete fracture network (DFN) modeling are tools that facilitate the choice of the required volume.

Grout penetration length has been considered as one of the main factors in establishing analytical solutions aimed at the avoidance of unwanted deformations due to jacking. In studies by Brantberger et al. (2000) and Gothäll and Stille (2009), both elastic and irreversible jacking were linked to grout pressure and grout spread, and the reaction of the rock mass was studied and characterized. Dalmalm and Stille (2003) showed how measurement of the grout flow and grout pressure could be used to interpret the depth of penetration around a tunnel by semi-empirical methods. Analytical solutions for the estimation of the grout spread in real time were formulated through the work done by Gustafson and Stille (2005). This approach may be called "Real Time Grouting Control" (RTGC). The efficiency of this theoretical approach in predicting grout flow and estimating grout spread has been examined in a number of case studies in different projects (Fransson et al., 2012; Kobayashi et al., 2008; Rafi et al., 2012; Tsuji et al., 2012). An alternative solution of two-dimensional grout spread has also been proposed by El Tani (2012).

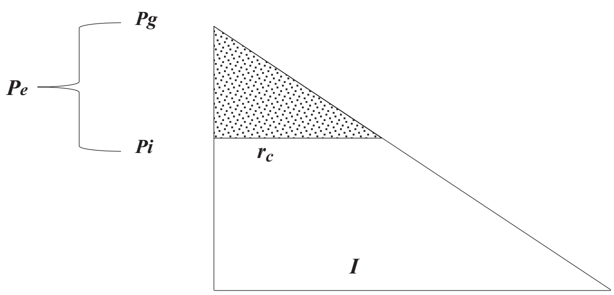

Fig. 2. Excess pressure (P_e) is due to the difference between grouting pressure and critical pressure (dotted zone).

These analytical determinations of grout penetration versus time provide an interesting opportunity, firstly for developing an understanding of jacking mechanism and secondly for the formulation of a theoretical approach for estimating deformation of fractures as a function of applied pressure and grout spread in real time. (Stille et al., 2012).

Against this background, the objective of the research work reported here is to validate the applicability of RTGC. In this paper, the efficiency of this theory in identifying the onset of jacking and estimating the state of the fracture in real time is examined. Case records from two grouting projects are studied by comparing deviations in the recorded flow data with the predictions of RTGC method, to establish whether jacking occurred. Furthermore, a methodology to establish the appropriate grouting pressure from the required penetration length is proposed. By comparing the outcomes with the initially recommended pressures from the empirical methods, the effectiveness of the RTGC method is discussed.

The implementation of theoretical approach to the establishment of fracture deformation from pressure and grout spread based on real data from grouting projects, and the consequent optimization of grouting pressure can be considered to be a further

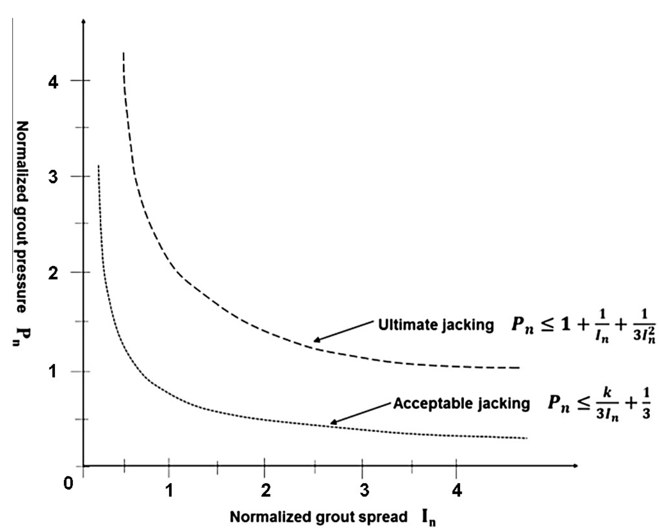

Fig. 4. Maximum normalized pressure as a function of normalized grout spread for both the ultimate limit state (Eq. (1)) and the acceptable limit state (Eq. (2)). The curves are calculated for $P_w = 0$ (after Stille et al. (2012)).