Tunnelling and Underground Space Technology 49 (2015) 174–187

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Basic mechanism of elastic jacking and impact of fracture aperture change on grout spread, transmissivity and penetrability

Jalaleddin Yaghoobi Rafi *, Håkan Stille

Royal Institute of Technology, Brinellv. 23, SE-100 44 Stockholm, Sweden

A R T I C L E I N F O

Article history:
Received 29 May 2014
Received in revised form 29 March 2015
Accepted 1 April 2015

Keywords:
Elastic jacking
Grout spread
Transmissivity
Grouting pressure
Fracture stiffness

A B S T R A C T

One of the most important parameters in the grouting of rock fractures is the applied pressure. This produces the driving force on the Bingham group material that causes it to penetrate the fracture. However, deciding the optimum pumping pressure is challenging. Using too high a pressure not only causes the grout to spread beyond the desired area, but, if it exceeds the minimum in situ stress in the rock mass, may also cause jacking of the fractures. This may lead to uncontrolled uplift. With a lower grout pressure, this "ultimate state" (jacking) can be avoided, although the pressurized grout still may induce smaller elastic deformations during pumping, and these may become irreversible when the grout has hardened. In previous studies, various theoretical approaches to distinguish the onset of these elastic and non-elastic deformations have been described and evaluated. However, the merits and disadvantages of theoretical approaches in general have been questionable. In the current study, the basic mechanism of elastic jacking is described, and its negative consequences are analyzed and quantified. These are the prolongation of grouting time, and the reduction in sealing efficiency. The role of an increased grouting pressure is evaluated by considering its positive effect in improving the penetrability and comparing this with the potential negative consequences. Case studies from two projects (the THX and Citybanan projects) are studied to examine the efficiency of the work that was carried out on site. The results indicate a high-applied pressure can have negative effect on the grouting procedure, and that this effect is significant in fractures situated in weak rock at shallow depth. It is concluded that unwanted fracture deformations and their negative consequences can be eliminated by defining appropriate stop criteria in advance of grouting, and confirming their suitability during pumping by the use of theoretical approach presented here. In general, this will allow the use of lower pump pressure and allow better control of the grout spread.

1. Introduction

During the grouting of fractured rock, the grout pressure induces stresses on the walls of the fracture. When these stresses exceed the in situ stresses, an excessive load on the rock mass is created. This leads to the deformation of the half spaces bounding the fractures. If the grouting induced load on the rock mass is allowed to become as high as the bearing capacity, ultimate jacking will occur (Brantberger et al., 2000). At pressures much lower than this, the deformations are elastic.

Based on the spread of grout and the grout pressure, Gothäll and Stille (2009) introduced a theoretical elastic jacking limit, above which the fractures will start to dilate. Subsequently, a methodology to distinguish the onset of jacking in real time was presented by Rafi and Stille (2014), where the distance of penetration, estimated by use of the Real Time Grouting Control Method (see Gustafson and Stille, 2005), is discussed in relation to theoretical elastic jacking limit. They showed that the pumping pressure and grouting time could be optimized to reach the required grout spread while avoiding any deformation in the fractures. As discussed by Gothäll and Stille (2009), controlling the pumping pressure in order to avoid elastic jacking and thereby improving the efficiency of production grouting, is challenging. In many grouting applications, using a high pressure in order to cause elastic jacking deliberately has been suggested in order to increase penetrability in finer fissures (Lombardi and Deere, 1993). However, where this produce large deformations, the soundness of this suggestion is questionable. Furthermore, in this case, the sealing efficiency of the grouting operation can be negatively affected as well.

The objective of this paper is to show how selection of grouting pressure is related to control of fracture deformation, and to

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

http://dx.doi.org/10.1016/j.tust.2015.04.002
0886-7798/

discuss the operational parameters to be considered in deciding the optimal pressure. For this purpose, the basic mechanism of elastic jacking during grouting is investigated. The excess volume of fracture void that is created by elastic jacking is estimated by establishing the profile of the fracture deformation and its correlation to the applied pressure. For a given grout volume at constant flow, the reduction in the radius of grout spread due to this increase in fracture volume is estimated, as well as the increase in transmissivity of the rock mass outside the grouted zone, as a result of the extension of fracture deformation. The results are discussed by considering the enhancement of penetrability caused by this elastic deformation. This approach is applied to field data from two grouting projects, by examining the effect of adjusting the grout pressure in order to limit both elastic jacking and the distance that grout spread. Finally, based on this investigation, the possibility of optimizing grouting pressure by using the theoretical approach is discussed.

2. Theoretical approach

2.1. Basic mechanism of jacking

Several experiments have been carried out in order to study the elastic behavior of the fracture (see for e.g. Barton et al., 1985; Hopkins, 2000). The results indicated that a nonlinear opening and closing of the fractures would occur during loading and unloading. This could be explained by considering the fracture as a pre-loaded mechanical coupling between two rock volumes. An internal pressure from the grout acting within fracture can therefore be seen as a reduction in the pre-existing compressive load, i.e. an unloading of the fractured rock. As discussed by Gothäll and Stille (2009), the "Contact pressure hypothesis" suggests that either no, or only a very small deformation occurs until the asperities lose their contact. This corresponds to the unloading stress-opening curves for joints, observed through extensive experiment by Bandis et al. (1983).

Based on the above, the stress–deformation behavior during unloading is illustrated in Fig. 1. In applying pressures smaller than the critical pressure (P_i), the induced deformations will be relatively small and can be assumed as zero as long as the asperities do not lose their contacts (zone 1). Subsequently, the stress–deformation behavior becomes independent of the fracture stiffness if pressurizing of the fracture is continued (Rutqvist and Stephansson, 1996) i.e. the fracture opens up. Beyond this point

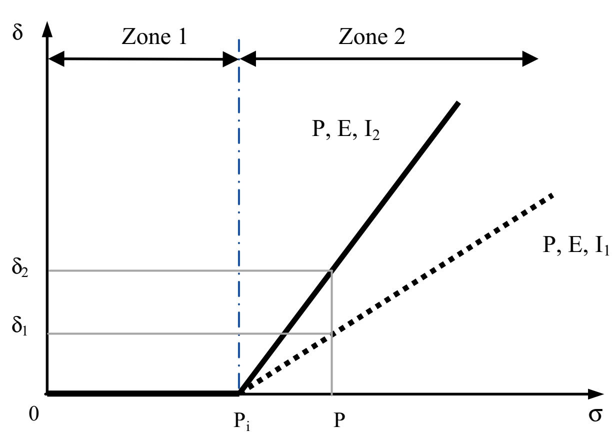

Fig. 1. The increase of stress with no deformation in zone 1 corresponds to the unloading of stress-opening curves of joints reported by Bandis et al. (1983). As soon as grout pressure exceeds the critical pressure, the fracture opens up. In continuing the grouting, zone 2, only the stiffness of the rock mass is considered and this stiffness is governed by the penetration distance of the Bingham fluid.

(zone 2), continued deformation of the fracture not only depends on the injection pressure and modulus of elasticity of the rock mass, but also on the radius of the grout spread (I). Thus, in grouting with the same pressure and at larger grout spread ($I_2 > I_1$), the stiffness will be reduced, i.e. the joints continue dilate as the grout spread further, despite constant applied pressure.

To quantify the amount of this deformation along the fracture, it has been approximated as the deformation of a half infinite space, for which the following expression was obtained by Gothäll and Stille (2009) at a sufficiently large distance from the borehole:

$$\Delta a(r) = \frac{4}{3}\frac{P_e r_c^2}{Er}(1-\vartheta^2) \tag{1}$$

where P_e is the difference between the grout injection pressure (P_g) and the critical pressure (P_i), and is called the "excess pressure", E is the elastic modulus of the rock mass, v is the Poisson's ratio, r_c is the radius of the zone over which the excess pressure (P_e) acts on the fracture wall, and r is the radial distance from the borehole. For the case of an infinite solitary fracture within an infinite homogenous rock mass, this deformation is nearly constant along the radius of r_c and thus can be written as Eq. (2). Beyond this distance ($r > r_c$), deformation is extended along the fracture due to the redistribution of the load in neighboring areas, and then dies away at a further distance (Fig. 2).

$$\Delta a_j = \frac{4}{3}\frac{P_e r_c}{E}(1-\vartheta^2) \tag{2}$$

By assuming that the pressure drop will be linear with the grout spread, following relation between r_c and the distance that grout spread (I) can be obtained:

$$I = \frac{P_g}{P_e} r_c \tag{3}$$

2.2. Jacking consequences

2.2.1. Increase of grout penetrability

Deformation of the fracture might be beneficial since it may improve penetrability of grout. It has been remarked by many previous researcher e.g. Ashikhmen and Peronina (2001) that the ability of cement grout to penetrate an opening with small dimension, say a fraction of a millimeter, depends on the dimension of the granules of cement and the size of the opening. It is obvious that an identical cement grout will penetrate more easily in a larger fracture. To evaluate the penetrability properties of a grout mix, Eriksson and Stille (2003) introduced the concept of limiting boundaries, with the "minimum aperture ($b_{\min}$)" being that through which no grout can enter an opening and the "critical aperture (b_{critical})" being that trough which an infinite amount of grout can pass. Since grout can freely penetrates into a fracture with aperture size of b_{critical} or larger, elastic jacking will only affect the grout flow up to the point where the total aperture size after dilation goes up to b_{critical}. Results from different tests by Eriksson et al. (2004) and Draganović and Stille (2011) indicate that the critical aperture is rarely larger than twice of the minimum aperture that the grout mix can penetrate. Thus, enlarging this minimum fracture aperture to more than twice its initial size will not improve penetrability (Fig. 3).

2.2.2. Reduction in the sealing efficiency of grouting work

For the pre-grouting of tunnels, the target permeability of the surrounding rock mass is likely to be related to restricting the ingress of water, based on specified targets relating to either the excavation or the operation of tunnel. In dam structures, reducing the permeability of the dam foundation by the construction of a grout curtain frequently is necessary to ensure the stability and