Journal of Rock Mechanics and Geotechnical Engineering xxx (2017) 1–18

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Roughness evaluation in shotcrete-lined water tunnels with invert concrete based on cases from Nepal

Chhatra Bahadur Basnet*, Krishna Kanta Panthi

Department of Geosciences and Petroleum, Norwegian University of Science and Technology, Sem Saelands Vei 1, NO-7491, Trondheim, Norway

ARTICLE INFO

Article history:
Received 18 April 2017
Received in revised form
19 June 2017
Accepted 18 July 2017
Available online xxx

Keywords:
Shotcrete-lined water tunnels
Friction loss
Physical and hydraulic roughnesses
Tunnel over-break

ABSTRACT

Most of the existing roughness estimation methods for water tunnels are related to either unlined or concrete/steel-lined tunnels. With the improvement in shotcrete technology, advancement in tunneling equipment and cost and time effectiveness, future water tunnels built for hydropower projects will consist of rock support with the extensive use of shotcrete lining in combination with systematic bolting and concrete lining in the tunnel invert. However, very little research has been performed to find out tunnel surface roughness for shotcrete-lined tunnels with invert concrete, which is important in calculating overall head loss along the waterway system to achieve an optimum and economic hydropower plant design. Hence, the main aim of this article is to review prevailing methods available to calculate tunnel wall roughness, and to use existing methods of head loss calculation to back-calculate roughness of the shotcrete-lined tunnels with invert concrete by exploiting measured head loss and actual cross-sectional profiles of two headrace tunnels from Nepal. Furthermore, the article aims to establish a link between the Manning coefficient and the physical roughness of the shotcrete-lined tunnel with invert concrete and to establish a link between over-break thickness and physical roughness. Attempts are also made to find a correlation between over-break thickness and rock mass quality described by Q-system and discussions are conducted on the potential cost savings that can be made if concrete lining is replaced by shotcrete lining with invert concrete.

1. Introduction

The waterway tunnels represent the most significant source of construction cost for hydropower projects, especially for run-of-the-river plants. Reducing and optimizing the cost of waterway systems is therefore a major issue to make hydropower projects financially attractive. One of the economic solutions is to use unlined or shotcrete-lined pressure tunnels or combination of both for the waterway system if the rock mass and applied shotcrete and/or systematic bolting guarantee long-term stability and safety (Panthi, 2015). Originally, the application of unlined shafts and tunnels as waterway systems came in practice in Norway with the philosophy that accepts minor falls of rock blocks during the operation period provided that head loss is within permissible limits (Broch, 1982). The basic criteria to be satisfied for unlined or shotcrete-lined pressure shafts and tunnels are safety against hydraulic splitting, hydraulic efficiency (frictional head loss) and long-term stability (Brekke and Ripley, 1987; Benson, 1989). Frictional head loss depends on both cross-sectional area and roughness of tunnel periphery in consideration (Rahm, 1958), because rougher tunnel wall surfaces will result in higher head loss and larger cross-sectional areas result in smaller head loss. An alternative way to reduce the head loss can be the use of concrete or steel lining to make the tunnel surfaces smoother without increasing tunnel size. However, lining a tunnel with concrete or steel will demand considerable additional cost (Huval, 1969; Westfall, 1996).

Tunnel shape also influences hydraulic efficiency of the water tunnel. In tunnel boring machine (TBM) tunneling, the tunnel cross-section is circular (i.e. hydraulically ideal shape) with smooth rock surfaces. However, it is not always feasible to use TBM as an excavation method since the success of TBM application is largely dependent on the geological conditions and length of the tunnel to be excavated. Hence, the drill-and-blast method of tunnel excavation is popular and extensively used due to flexibility in making decisions if unforeseen geological conditions arise and it can be

---

* Corresponding author.
E-mail address: Chhatra.basnet@ntnu.no (C.B. Basnet).
Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2017.07.006

Please cite this article in press as: Basnet CB, Panthi KK, Roughness evaluation in shotcrete-lined water tunnels with invert concrete based on cases from Nepal, Journal of Rock Mechanics and Geotechnical Engineering (2017), https://doi.org/10.1016/j.jrmge.2017.07.006

used in any length of tunnel to be excavated, provided that ventilation requirements during construction are met. However, tunnel walls excavated using drill-and-blast method have an undulating surface of varying smoothness and the shape of tunnel will be determined mostly by construction necessities and easiness (Lysne et al., 2003). The most practical tunnel shapes in drill-and-blast tunneling are inverted D and horse-shoe (Cuesta, 1988; Panthi, 2015). In waterway tunnels, excavated tunnel profiles may either be left unlined or shotcrete-lined or concrete/steel-lined (or a combination of different linings). The shotcrete-lined tunnels end up more or less with the excavated shape and surface as shown in Fig. 1.

As seen in Fig. 1, there are undulations in the contour surface in a tunnel excavated using the drill-and-blast method due to the presence of grooves and projections. The frequency distribution and amplitude of these undulations signify resistance to water flow and are defined by the term surface/physical roughness. These undulations are the result of over-break of the rock mass beyond the designed tunnel profile (Maerz et al., 1996). The larger the over-break area is, the more the tunnel surface will be undulated and rough. Hence, over-break is the key parameter to define roughness of the tunnel surface. According to various researches, over-break in drill-and-blast tunnels is the result of look-out and deviation in contour holes, blasting energy, rock mass condition and in situ stress situation (Nilsen and Thidemann, 1993; Mandal and Singh, 2009; Kim and Bruland, 2015). Longer blast rounds develop greater longitudinal over-break leading to an increase in roughness of the tunnel surface. Similarly, the rock mass condition influences over-break intensity and roughness. In Fig. 2a, the blasted tunnel surface is relatively smooth in the case of a homogeneous rock mass, whereas, if rock mass is jointed, the surface roughness is partially determined by the jointing pattern (Fig. 2b). In addition, there might be some localized enlarged over-break due to the presence of faults or weakness zones (Figs. 1b and 2c), which will further increase the roughness. Fig. 2a is seldom achieved in the jointed rock mass, thus Fig. 2b and c represents the most common contour profile types in blasted tunnels. Over-break in Fig. 2a and b may be defined as normal over-break, whereas localized enlarged area in Fig. 2c may be expressed as excessive over-break. Such localized enlarged areas may also be formed due to stress induced rock spalling and bursting in hard rock (Panthi, 2012).

Now the question arises as how the physical roughness can be used to calculate frictional head loss along the waterway tunnel. Both the Darcy–Weisbach and Manning formulae use coefficient of resistance, known as hydraulic roughness, in order to calculate frictional head loss. However, the hydraulic roughness in the equations is not equivalent to the physical roughness directly measured from the tunnel surface. Before 1980, according to Bishwakarma (2012), it was a common practice to calculate hydraulic roughness from the relative variation of cross-sectional area along the tunnel length using different methods proposed by Rahm (1958), Priha (1969), Reinius (1970), Wright (1971) and others. Later in the 1990s, the concept was updated with the introduction of physical roughness of the tunnel, which is related to both surface undulations and area variation (Bruland and Solvik, 1987; Ronn and Skog, 1997), and the physical roughness was converted to the hydraulic roughness in order to fit into the head loss equations. It is a common practice to calculate hydraulic roughness using the relationship proposed by Colebrook (1958) considering physical roughness as equivalent sand roughness. Bruland and Solvik (1987) extended their research and proposed a new relationship between physical roughness and hydraulic roughness where the physical roughness in their definition does not correspond to the sand roughness. On the other hand, the total physical roughness defined by Ronn and Skog (1997) corresponds to the sand roughness and fits into Colebrook (1958)'s equation. More recently, attempts have also been made to relate measured physical roughness to hydraulic roughness for bored tunnels (Pegram and Pennington, 1998; Hákonardóttir et al., 2009). Regardless of the type of method used, a correct definition of physical roughness and its relation with hydraulic roughness are the key issues to define unlined or shotcrete-lined tunnel hydraulics.

Existing methods of estimating tunnel roughness are used only after the tunnel is excavated and the geometrical data of actual tunnel surface are available. In parallel to these methods, attempts have also been made to predict tunnel roughness before tunnel excavation based on over-break in tunnels (Colebrook, 1958; Huval, 1969; Priha, 1969; Kim, 2009), even though it is difficult to define over-break intensity and its relation to physical roughness. In this perspective, this article attempts to establish a new relationship between physical roughness and over-break thickness by analyzing actual tunnel profiles of the shotcrete-lined headrace tunnel of the Chilime hydropower project (CHP) in Nepal. Similarly, the article also attempts to establish a correlation between physical roughness and the Manning coefficient (hydraulic roughness) and proposes modifications on the methods proposed by Colebrook (1958) and Solvik (1984). Furthermore, the modified equations are used to predict roughness and hence the head loss and results are

a. Relatively good quality tunnel contour (Upper Tamakoshi Project, Nepal)

b. Relatively poor quality tunnel contour with excessive over-break (Khimti Project, Nepal)

Fig. 1. Tunnel contour quality after blasting and shotcreting.

Please cite this article in press as: Basnet CB, Panthi KK, Roughness evaluation in shotcrete-lined water tunnels with invert concrete based on cases from Nepal, Journal of Rock Mechanics and Geotechnical Engineering (2017), https://doi.org/10.1016/j.jrmge.2017.07.006