Spatial Variability of Shotcrete Thickness in Design of Rock Tunnel Support

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Abstract: To account for uncertainties in design of shotcrete support against unstable blocks located in the periphery of an underground opening, reliability-based methods can be used. With this method, the shotcrete layer's support capacity is accounted for by defining suitable probability distributions for all relevant input parameters. To define them, understanding of their spatial variabilities is important because its spatial correlation might enable variance reduction, if the common assumption is made that the shotcrete support capacity is governed by the average value of a set of parameters. In this paper, we show how the variation of the spatial mean value for shotcrete thickness can be reduced using variance reduction techniques. We exemplify the procedure using the spatial variability of the shotcrete thickness, which was quantified from a laser scanning of a tunnel before and after shotcrete application. The paper illustrates and discusses how the spatial variability of the measured shotcrete thickness affects its statistical distribution and the calculated probability of shotcrete failure.

Keywords: Spatial variability; shotcrete thickness; rock tunnel; tunnel support; reliability-based design.

1 Introduction

In design of underground excavations in hard brittle rock, a common failure mode that must be accounted for is falling or sliding blocks. A common support measure to secure these blocks is to apply a thin shotcrete layer to the excavation's rock surface and systematically install rockbolts. The main idea of this support measure is to use the rockbolts to suspend larger blocks and the shotcrete to keep smaller blocks in place between the rockbolts.

To verify the shotcrete layer's ability to suspend these smaller blocks, a number of failure modes must be considered: direct shear, punching shear, and flexural failure of the thin shotcrete layer, all of which are governed by the existence of sufficient adhesion in the rock–shotcrete interface along the circumference of the unstable block (Holmgren 1992; Barrett and McCreath 1995; Banton et al. 2004; Bjureland et al. 2019). To consider these failure modes, suitable limit state functions need to be defined and analyzed with reliability-based methods (Bjureland et al. 2019). By doing so, the uncertainty in each parameter can be accounted for and structural safety can be ensured. However, in order to do this, all parameters must be defined in terms of their respective mean value, standard deviation, and probability distribution type.

Based on a large number of measurements executed as a part of the control program for a tunnel construction project in Stockholm, Sweden, Bjureland et al. (2019) derived statistical data for the main parameters incorporated in the design of shotcrete support of small unstable blocks. The parameters were adhesion in the rock–shotcrete interface, a, the thickness of the applied shotcrete layer, t, the shotcrete's flexural tensile capacity, $f_{\mathrm{ctm,fl}}$, and the shotcrete's residual flexural tensile capacity, $f_{\mathrm{ctm.fl}}^{\mathrm{re}}$. For all parameters, a normal distribution was found to be suitable, except for t where a lognormal distribution was preferred. The variability of each parameter was found to be relatively large (the coefficient of variation equaled approximately 10-40%). However, one issue with the derived mean values and standard deviations is that the applied measurement methods only allowed for quantification of representative probability distributions with respect to the scale of the tunnel. Since the mean and standard deviation of e.g. t in between four rockbolts (i.e. the area of interest in the design of shotcrete against unstable blocks) do not necessarily correspond to those across the whole tunnel, due to the spatial correlation, a corresponding adjustment to Bjureland et al.'s (2019) derived standard deviations is important. It should be noted that the possibility of accounting for the spatial variability requires that the common assumption of a mean-value-driven system is made (Holmgren 1992; Barrett and McCreath 1995; Banton et al. 2004), the validity of which is currently being investigated as a separate part of this research project.

Presuming the validity of a mean-value-driven mechanical system, we discuss in this paper how the spatial correlation of a parameter can be accounted for in design of shotcrete support, using reliability-based methods and variance reduction techniques (e.g., Vanmarcke 1977). The paper also illustrates how this spatial correlation of t affects its probability distribution and the probability that the load from the unstable block exceeds the shotcrete's bending moment capacity (flexural failure). The statistical distribution of t is described based on

Proceedings of the 7th International Symposium on Geotechnical Safety and Risk (ISGSR)
Editors: Jianye Ching, Dian-Qing Li and Jie Zhang

Published by Research Publishing, Singapore.
ISBN: 978-981-11-2725-0; doi:10.3850/978-981-11-2725-0_IS16-5-cd

data collected from a new railway tunnel project in Stockholm, Sweden (The Stockholm City Line). The variability of the mean value for t is reduced using spatial correlation data collected from the laser scanning of the Äspö Hardrock laboratory tunnel in Oskarshamn, Sweden.

2 Shotcrete Support of Unstable Blocks in Rock Tunnels

To verify a shotcrete's capacity to secure unstable blocks, analytical calculations are commonly used (e.g., Barrett and McCreath 1995; Nilsson 2003; Lindfors et al. 2015). In these analytical calculations, the shotcrete support is generally analyzed by assuming that the shotcrete acts as a structural system of which the load-carrying capacity is governed by three main failure modes, i.e. direct shear, punching shear, or flexural failure (Figure 1) (Barrett and McCreath 1995; Bjureland et al. 2019).

In this system, failure is conditioned on and correlated to the existence of sufficient adhesion in the rock–shotcrete interface along the circumference of the unstable block (Bjureland et al. 2019). If the adhesive capacity along the circumference of the unstable block is sufficient to carry the weight of the block, the shotcrete's capacity is determined by its ability to sustain direct shear forces originating from the weight of the unstable block (Barrett and McCreath 1995; Bjureland et al. 2019). On the other hand, if the adhesive capacity is insufficient, the shotcrete's capacity is determined either by its resistance to punching shear of the rockbolts, or by its ability to resist bending moments through its bending moment capacity, R_{fl} (Figure 1). In Bjureland et al. (2019), the governing failure mode was found to be flexural failure. Therefore, in this paper, we limit the analysis to this particular failure mode.

The R_{fl} can be calculated using different approaches, depending on for example whether plain or fiber-reinforced shotcrete is used (Holmgren 1992; Barrett and McCreath 1995; Banton et al. 2004; Bjureland et al. 2019). If plain shotcrete is used, one approach is to estimate the R_{fl} based on its flexural tensile capacity, $f_{\mathrm{ctm,fl}}$, i.e. its elastic limit at which cracking starts to occur (Banton et al. 2004). Per meter width of shotcrete layer, R_{fl} can be calculated as (e.g., Barrett and McCreath 1995; Banton et al. 2004):

$$R_{\mathrm{fl}} = \frac{f_{\mathrm{ctm,fl}} t^2}{6}. \qquad (1)$$

If fiber-reinforced shotcrete is used, it is common practice to estimate the R_{fl} by accounting for the increased toughness introduced by the fibers (Holmgren 1992). However, for simplicity, we neglect this effect in this paper. The R_{fl} is sufficient if it can resist the M caused by the weight of the block. The bending moment has been calculated using Kirchhoffs plate theory (Timoshenko and Woinowsky-Krieger 1959; Ventsel and Krauthammer 2001) as:

$$M = 0.0469 q s^2, \qquad (2)$$

where s is the center to center distance between the rockbolts; q is an evenly distributed load, here assumed equal to W / s^2.

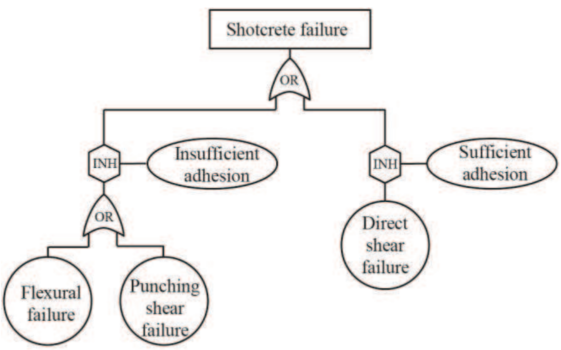

Figure 1. Fault tree representing the structural system of shotcrete support (© Bjureland et al. 2019, CC–BY 4.0, https://creativecommons.org/licenses/by/4.0).

3 Reliability-Based Methods

Reliability-based methods can be used to ensure a sufficient safety margin against failure. In these methods, uncertainties are accounted for by first defining a limit state function, $G(\boldsymbol{X})$, that contains all relevant uncertain parameters, $\boldsymbol{X}$, and then calculating the probability of limit state exceedance by evaluating the multidimensional integral over the unsafe regions, D_i (Melchers 1999):

$$p_\mathrm{f} = \mathcal{P}\left[G_i\left(X\right)\leq \;\right] = \int\limits_{\cup\cap D_i \in X} \dots \int f_\mathrm{X}\left(X\right)\mathrm{dx}. \tag{3}$$

Note that this multidimensional integral in many cases is impossible to solve analytically. Therefore, approximate or numerical methods such as Monte Carlo simulations are often used to overcome this problem. To do this evaluation, each parameter in $\boldsymbol{X}$ must be described in terms of their spatial variability. Essentially, for each parameter of interest, this can be done using three variables: mean, standard deviation, and the scale of fluctuation, θ. The θ is a measure that describes the distance within which a strong spatial correlation between two points exists (Vanmarcke 1977). It is commonly estimated by fitting a theoretical correlation function, $\rho(\tau)$, to a set of data for a parameter of interest (e.g., Lloret-Cabot et al. 2014), which in our case is e.g. the shotcrete thickness. The θ then defines the correlation between two points separated by a distance τ. A common correlation function is the Gaussian, which for the correlation between two points in the *z* direction is expressed as (Shi and Stewart 2015):

$$\rho\left(\tau_\mathrm{z}\right) = \exp\left(-\pi\left(\frac{\left|\tau_\mathrm{z}\right|}{\theta_\mathrm{z}}\right)^2\right), \tag{4}$$

where $\tau_\mathrm{z} = z_i - z_j$ is the distance between the two points i and j in the z direction; θ_z is the scale of fluctuation in the z direction.

One of the main benefits of knowing θ is the possibility to perform variance reduction on the parameter of interest, because the variance reduction factor, Γ, depends on θ in relation to the geometrical size of the studied area (i.e., the shotcreted area between four rockbolts). For a parameter with equal θ in two directions, *x* and *y*, and equal geometrical size, Δ, in the same directions, i.e $\Delta x = \Delta y = \Delta$, the Γ can be calculated as (Vanmarcke 1977):

$$\Gamma\left(\Delta x, \Delta y\right) = \left(\frac{\theta_\mathrm{x}\theta_\mathrm{y}}{\Delta x \Delta y}\right)^{\frac{1}{2}} = \frac{\theta}{\Delta}, \tag{5}$$

where θ_x and θ_y are the respective scale of fluctuations in the x and y directions. Note that Eq. 5 is only valid for $\theta \leq \Delta$. If $\theta \geq \Delta$, then $\Gamma = 1$. The effect of Γ on the standard deviation, σ, of the mean value of the parameter of interest is:

$$\sigma_\mathrm{r} = \Gamma\sigma, \tag{6}$$

where σ_r is the reduced standard deviation.

4 Calculation Example

To illustrate the effect of variance reduction on the design of shotcrete support, a calculation example is presented in the following. Variance reduction is limited to being performed on t, since it is one of the most important parameters affecting the shotcrete failure probability, and since its variation over the area between four rockbolts might be significant (Klaube 2018). The Γ for different magnitudes of θ and common magnitudes of s used in rock tunnels are illustrated in Figure 2. Clearly, considerable variance reduction is possible when θ is small in relation to s (i.e., the distance between the rock bolts).

As a basis for the calculations, statistical moments and suitable probability distributions for the shotcrete support along with the block size and variability have been chosen based on data collected from The City Line Project in Stockholm Sweden (Bjureland et al. 2019). The scale of fluctuation for thickness, θ_t, was assumed to be 0.8 m in accordance with the results presented by Klaube (2018), which were obtained by collecting data from the laser scanning of the Äspö Hardrock laboratory tunnel before and after shotcrete was applied. The θ_t was quantified by evaluating t in a fine grid pattern along one of the walls and then fitting a theoretical correlation function to the evaluated values of t. The input data used in the calculation example can be seen in Table 1.

It should be noted here that the assumption that θ_t quantified at Äspö Hardrock laboratory tunnel is representative for θ_t at the The City Line Project to some extent is incorrect, since the conditions at Äspö Hardrock Laboratory is not exactly the same as those in The City Line Project. However, since the purpose of this calculation example is to illustrate how θ_t affects the probability distribution of t and the probability that the load from the unstable block exceeds the shotcrete's bending moment capacity, this assumption is considered to be reasonable.

The limit state function, G_{fl}, for evaluating the probability of exceeding R_{fl}, can be expressed as (Bjureland et al. 2019):

$$G_{fl} = R_{fl} - M. \tag{7}$$

To approximate the integral in Eq. 3, Monte Carlo simulations with 10 000 000 realizations were utilized. The p_f is approximated by counting how many of the realizations that satisfy $G_{fl} < 0$ in relation to the total number of realizations. The calculated p_f before variance reduction equaled approximately 0.07.

Using Eq. 5, the variance reduction factor was calculated to be $\Gamma = 0.53$. The effect of applying this factor on the standard deviation of the mean shotcrete thickness can be seen in Figure 3. The calculated p_f after variance reduction equaled approximately 0.0055.

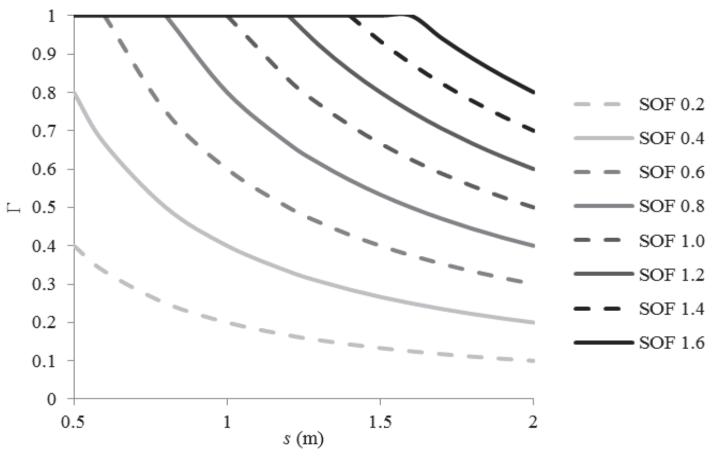

Figure 2. Effect of scale of fluctuations, θ, (denoted SOF in the Figure) on calculated variance reduction factors for different center distances between rockbolts, s.

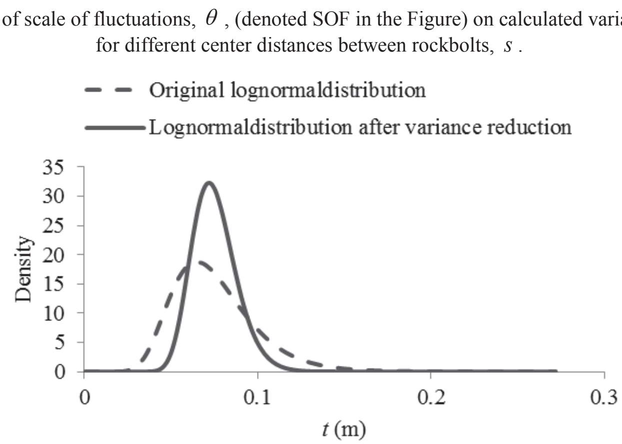

Figure 3. Probability distributions for shotcrete thickness before and after variance reduction.

Table 1. Input data for the calculation example.

Parameter	Symbol	Unit	Distribution	Sample mean	Sample standard deviation
Shotcrete					
Shotcrete thickness	t	[mm]	Lognormal	75	24
Bending tensile capacity	$f_{\mathrm{ctm,fl}}$	[MPa]	Normal	6.8	0.84
Rockbolts					
Center to center distance	s	[m]	–	1.5	–
Rock mass					
Unit weight of rock mass	γ_{r}	[kN/m³]	–	27.00	–
Volume of block	V	[m³]	Normal	1.98	0.36

5 Discussion

Design of shotcrete support against small unstable blocks can be performed using reliability-based methods. To fully account for the effect of the spatial variability of t on the calculated shotcrete failure probability, the θ_{t} needs to be quantified (given that the assumption of a mean-value-driven system can be confirmed). As discussed by Klaube (2018), such quantification can be done based on laser scanning data from the tunnel walls before and after shotcrete application. As shown in the performed calculation example, the variance reduction can potentially have a large effect, especially when θ_{t} is considerably smaller than s . If this is not accounted for, the designed shotcrete support will become overly conservative.

In practice, as suggested by Bjureland et al. (2019), variance reduction might also be possible to perform on other input parameters than t . This requires a quantification of the spatial variability of each parameter. However, this is generally not possible to perform with the data obtained from the standard measurement techniques used in today's tunnel projects. This is a challenge for future research.

In addition, in the calculation example, the θ_{t} was retrieved from the work performed by Klaube (2018), who, however, only quantified the θ_{t} for a relatively short section of one of the walls in the Äspö Hardrock laboratory tunnel, Oskarshamn, Sweden. Therefore, we recommend more extensive studies under different geological conditions and tunnel geometries to quantify θ_{t} .

6 Conclusions

In this paper, we discuss how the scale of fluctuation can be utilized to reduce the variance of the mean shotcrete thickness between rockbolts, given that the assumption of a mean-value-driven system can be validated. A calculation example is performed to illustrate the effect from variance reduction on the calculated probability of shotcrete failure. The example shows that the scale of fluctuation has a large effect on the calculated failure probability. However, spatial variability of other parameters may also affect the shotcrete's support capacity. Therefore, this needs to be further studied.

Acknowledgements

The authors acknowledge the Swedish Transport Administration for supplying the data studied in this paper and the funders of the TRUST project (www.trust-geoinfra.se) for their support of the research presented: the Rock Engineering Research Foundation, BESAB, SBUF, SKB (Swedish Nuclear Fuel and Waste Management Co), and SVC (Swedish Hydropower Center, www.svc.nu). SVC has been established by the Swedish Energy Agency, Elforsk and Svenska Kraftnät together with Luleå University, KTH Royal Institute of Technology, Chalmers University of Technology and Uppsala University.

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