

## Analysis of Shotcrete Lining of Underground Tunnels

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### ABSTRACT

Shotcrete is a process where concrete is projected or “shot” under pressure, using a feeder or a “gun” onto a surface to form structural shapes including walls, floors, and roofs. The surface can be wood, steel, polystyrene, or any other surfaces that concrete can be projected onto. The surface can be trowel led smooth while the concrete is still wet. Shotcrete has high strength, durability, low permeability, excellent bond, and limitless shape possibilities. These properties allow shotcrete to be used as a structural material in most cases. Although the hardened properties of shotcrete are similar to conventional cast-in-place concrete, the nature of the placement process provides additional benefits, such as excellent bond with most substrates and instant or rapid capabilities, particularly on complex forms or shapes. In addition to building homes, shotcrete can also be used to build pools. The practice of underground tunneling shows that the degree of stability of tunnels is dependent on the state of the soil, rock mass, and shotcrete around the tunnel contour. The development in the urban or suburban areas leads to the construction of tunnels in all kinds of soil and rock. Meanwhile, the construction of tunnels in shallow depth or soft soils causes the ground to displace. The determination of soil and rock mechanical properties to assess the stability of New Austrian Tunnelling Method (NATM) tunnels and design the support system is one of the most important steps in tunnelling. This paper provides information pertaining to the safety and increase the stability of NATM tunnel before, during and after the operation of the tunnel. Therefore, the shotcrete process is a recognized method for cemented sandy silt stabilization, with the aid of high pressure shot concrete to increase the stability of tunnels.

**Keywords:** Shotcrete, concrete, tunnel stability, NATM, tunnel construction

### NOTATION

- $f_{c,0}$  = Asymptotic Uniaxial compressive strength of shotcrete for Time  $t = \infty$  (MPa);  
 $f_t$  = tensile strength of shotcrete (kPa);  
 $f_{t,t}$  = tensile strength of shotcrete at Time (MPa);  
 $f_{t,0}$  = Asymptotic tensile strength of shotcrete for Time  $t = \infty$  (MPa);  
 $H, D$  = rise and span of the intrados of a lining segment(m);  
 $H', D'$  = measured value of H and D respectively(m);  
 $H_i, D_i$  = rise and span of the arc AB(refer to Fig. 1) at time  $i$ , respectively (m);  
 $h$  = thickness of a cross section (m);  
 $b$  = width of a cross section (m);  
 $E_i$  = Elastic modulus of shotcrete at time  $i$  (kPa)

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- $E_0$  = Asymptotic elastic modulus of shotcrete at time  $t = \infty$  (MPa);
- $E_t$  = elastic modulus of shotcrete at time  $t$  (MPa);
- $e$  = eccentricity =  $M/N$  (m);
- $f_c$  = compressive strength of shotcrete at time  $t$  (MPa);
- $f_{c,t}$  = uniaxial compressive strength of shotcrete at time  $t$  (MPa);
- $I$  = moment of inertia of a cross section,  $I = bh^3/12$  ( $m^4$ );
- $t_i$  = time of measurement;
- $L_i, L_{i-1}$  = arc length of the central axis of a lining segment at time  $t_i$  and  $t_{i-1}$
- $M$  = bending moment (kN m);
- $N$  = Axial force (kN);
- $T$  = time (h);
- $\Delta \varepsilon_i$  = change in strain of the central axis of a lining segment from time  $t_{i-1}$  to  $t_i$ ,  $\Delta \varepsilon_i = (L_i - L_{i-1}) / L_{i-1}$ ;
- $\theta_i$  = central angle of the arc AB (refer to Fig. 1) at time  $t_i$ ,
- $\theta_i = 2 \arcsin(0.5D_i / \rho_i - 0.5h)$  (rad);
- $\lambda$  = time constant (I/H)
- $\xi, \zeta$  = random variables for the measurement errors in  $H$  and  $D$ , separately (m)
- $\rho_i, \rho_{i-1}$  = radius of curvature of the central axis of a lining segment at time  $t_i$  and  $t_{i-1}$ , separately (m);
- $\phi$  = stability factor for plain concrete compaction which is a function of the slenderness ratio of the component,  $\phi=1$  is often a suitable default setting for tunnel lining.
- $\alpha$  = eccentricity influence factor, which is a function of a ratio of a eccentricity of axial force over the section thickness of a component  $\alpha=1+0.648(e/h)-12.569(e/h)^2=15.444(e/h)^2$  (Chinese Railway Standard 2005);
- $\Delta M_i$  = change in bending moment from time  $t_{i-1}$  to  $t_i$  (kN m);
- $\Delta N_i$  = change in axial force from time  $t_{i-1}$  to  $t_i$  (kN m);

### INTRODUCTION

According to the New Austrian Tunnelling Method (NATM), shotcrete is applied onto the tunnel walls, constituting a thin flexible, closed shell, after excavation of a cross section of a tunnel. Deformations, as well as the loading of the lining, are continuously monitored during the construction, serving as input for decision-making process, following the closed control cycle “excavation–monitoring–parameter adaptation–excavation”. The objective of this control cycle is to optimize the tunnelling process with respect to cost, crew safety, and long-term tunnel stability. In this paper, questions related to this optimization process are addressed, whereby the influence of driving parameters and changes in the *in situ* geological and geotechnical conditions on the deformation and loading of the shotcrete lining are dealt with. Based on the realistic material models for shotcrete and ground, axisymmetric analyses, allowing for consideration of the three-dimensional nature of the tunnel excavation, were performed. The assumption of axisymmetry represents a good approximation of the static conditions of the tunnels with high overburden. The obtained results are presented in a dimensionless form so as to provide new insights into the complex ground-shotcrete interaction in the NATM tunnelling.

The New Austrian Tunnelling Method (NATM) is characterized by the continuous adaptation of driving parameters, such as unsupported excavation length (i.e. the distance between the tunnel face and shotcrete lining, excavation rate, etc.) to the observed response of the already-excavated part of the tunnel. The tunnel response is continuously monitored by the deformation measurements of the shotcrete lining of the tunnel and surface settlements, and the extensometer measurements

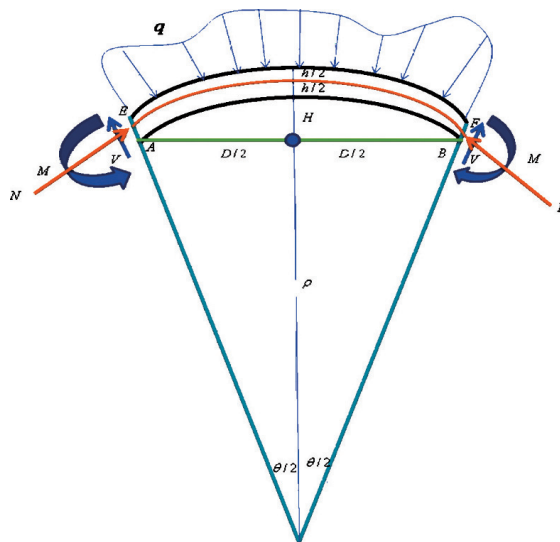
in the surrounding ground, as well as by the so-called hybrid analysis tools providing the evolution of the level of loading in the lining (Lackner & Mang, 2003; Shi, 2003). The available data are the input for adapting the driving parameters to ensure safety or/and to optimize the tunnelling process.

### PERFORMANCE FUNCTION

It is important to note that the initial failure of a cross section of the shotcrete lining is taken into consideration. The deformation of the lining is assumed to be small, linear, and elastic. For a concrete component without rebar's, there are two types of failures, namely, crushing due to axial compression, and cracking due to bending, which must be simultaneously avoided. Meanwhile, for a section subjected to a certain set of internal forces of the axial force  $N$ , bending moment  $M$ , and shear force  $V$ , only one type of failure may occur. Therefore, the performance function for the limit state against crushing and cracking can be expressed as:

$$g = \begin{cases} \varphi\alpha bhf_c - N & \text{for } e < 0.225h \\ 1.7\varphi bh^2 + Nh - 6M & \text{for } e \geq 0.225h \end{cases} \quad (1)$$

In order to evaluate the internal forces through displacements, let consider a lining segment as shown in *Fig. 1*. The segment can be a portion cut out of a lining, or the whole segment itself as often constructed when the non-full-face construction methods are adopted. The forces exerting on the segment can be represented by arbitrarily distributed loads acting on the extrados (the exterior curve of an arch), as well as the axial forces, bending moments, and shear forces acting at the two ends.



*Fig. 1: Lining of a segment*

Theoretically, all the external forces that are applied on the segment will contribute to its displacement (axially compressive deformation and bending deformation), whereas the internal forces within the segment can be found using the displacements only. In order to make this a reality, the following assumptions are employed:

1. Deflection of the lining is small and, within this amount of deformation, shotcrete is a linearly elastic material.
2. Cross sections of the segment remain plane and normal to its longitudinal axis, i.e. the assumption of the plane cross section holds.
3. Ignored is the deformation in the plane of cross section itself due to Poisson's ratio and the load acting on the extrados of the segment; in other words, the dimension of a cross section and the distance between any two points within the plane stay unchanged during deformation.
4. The neutral axis passes through the centric of the cross section area.
5. The presence of internal shear forces is disregarded, which means pure bending is adopted instead of actual non-uniform bending. A detailed investigation shows that for a rectangular beam with a slenderness ratio less than 10, the proportion of the deflection made by shear forces is not more than 2.2% (Timoshenko & Goodier, 1970) (De Figueiredo *et al.*, 1995; Sun, 2000). As for the lining segment ABFE (*Fig. 1*), the changes in the axial force and the bending moment under the assumption are made earlier and can be written as:

$$\Delta N_i = E_i b h \Delta \varepsilon_i \tag{2}$$

$$\Delta M_i = E_i I \left( \frac{1}{\rho_i} - \frac{1}{\rho_{i-1}} \right) \tag{3}$$

It is obvious that the segment does not necessary be in the shape of an arc during deformation. When it happens to be a straight line at the time of measurement *i*, for instance, the term  $1/\rho_i$  in Eq. (3) becomes zero. Another noteworthy item shown in *Fig. 1* is that the configuration of the arch-like segment is expressed by two values, namely the arch rise *H* and the arch span *D* of the intrados (i.e. the inner curve of an arch). Nonetheless, doing so does not mean the two values have to be measured directly. If the intrados of the lining are determined by the coordinates of a certain number of the measured points, a conversion from the coordinates to the two values must be performed so as to use the following formulas to compute the length and radius of curvature of the central axis.

In order to evaluate the length and the radius of curvature required in Eqs. (2) and (3), choosing a curve to interpolate the central axis of the segment is therefore necessary. It is important to note that different types of the interpolated curves give different values for the length and the radius of curvature. In this case, a circle is chosen and used to interpolate through three points: two end points and the apex (mid point) of the central axis of the segment. The interpolation ends up with the formulas to reckon the length and the radius of curvature of the central axis of the segment, as listed in the following:

$$\rho_i = \frac{1}{2} \left( H_i + \frac{D_i^2}{4H_i} \right) + \frac{h}{2} \tag{4}$$

$$L_i = \rho_i \theta_i \tag{5}$$

### PROBABILITY CHARACTERISTICS OF BASIC VARIABLES

It can be seen from Eqs. 1 to 5 that the performance function is related to certain variables, such as lining displacement (the rise and the span of the intrados of the lining segment), thickness of the lining and properties of shotcrete (namely, compressive strength, tensile strength, and the elastic modulus). Attention is paid to the probability characteristics of these variables hereinafter.

### UNCERTAINTIES IN THE DISPLACEMENT OF LINING

The main cause of uncertainties in the displacement of a lining is error in measurement. In general, this error does not vary considerably with the magnitude of the length surveyed. Hence, two random variables for the errors are introduced to represent the uncertainties in the measurement of the rise and the span of an arch-like segment, respectively.

$$\begin{aligned} H &= H' + \xi \\ D &= D' + \zeta \end{aligned} \quad (6)$$

In this case, two ways are usually used in practice to survey the displacement of the lining. The first way is to measure the relative displacement (convergence) between the two points on the intrados of a cross section of the lining. The instrument used in this measurement could be a convergence meter. The second way is to measure the displacement of a point on the lining with reference to a fixing point elsewhere. A level or a theodolite can be used to do this measurement. The statistical samples for  $\xi$  and  $\zeta$  can be obtained by taking measurements of the distance between two fixed points. In this case, the convergence measurement data of five cross sections from the Shengjie Tunnel are taken on the Jingjiao Express Way, which connects Jingcheng City in Shanxi Province to Jiaozuo City in Henan Province, to make the statistics of the uncertainties in  $\xi$  and  $\zeta$  (4). Meanwhile, the shotcrete lining at the five cross sections remained stable during the whole measuring period. The statistical results showed that  $\xi$  and  $\zeta$  were both of the normal distributions with zero means and standard deviations of 0.812 and 0.740, respectively.

The difference between the two standard deviations of  $\xi$  and  $\zeta$  is believed to be caused by different measurement methods used (i.e. the rise of the arch was measured with a level, whereas the span of the arch was scaled with a convergence meter). It is justifiable to take the same standard deviation for both  $\xi$  and  $\zeta$ , if the same measuring instruments are used somewhere else.

### UNCERTAINTIES IN THE THICKNESS OF LINING

Lackner & Mang (2003) studied the probability characteristics of the thickness of shotcrete linings. Their work came to the conclusion that, owing to overbreak, the actual thickness of shotcrete lining is often greater than the designed value. On the basis of their statistical results, it is therefore recommended that the excess thickness of shotcrete due to over break be ignored and the designed value are taken as the mean of lining thickness, with the coefficients of variation equivalent to 0.05, 0.07, and 0.09 for the ground of Classes III, IV, and V, respectively. The type of distribution of lining thickness came out to be normal.

### UNCERTAINTIES IN THE PROPERTIES OF SHOTCRETE (ORESTE, 2003)

The parameters for the properties of shotcrete include compressive strength, tensile strength, and elastic modulus. Compressive strength is often taken as a basic parameter of the material. Meanwhile, tensile strength and elastic modulus are assumed to have a linear relationship with compressive strength. In as much as shotcrete gains its strength as it cures, the strength growth of the material with time should be taken into account. The uniaxial compressive strength of shotcrete

during hardening can be expressed using the following negative exponential equation (Oreste, 2003):

$$f_{c,t} = f_{c,0}(1 - e^{-\lambda t}) \tag{7}$$

Suppose that the tensile strength and the elastic modulus have the same hardening rate as the compressive strength does, one will then find:

$$f_{t,t} = f_{t,0}(1 - e^{-\lambda t}) \tag{8}$$

$$E_t = E_0(1 - e^{-\lambda t}) \tag{9}$$

Up to now, the data for the strength of shotcrete at different curing ages are still rare. The stress measuring on shotcrete lining near the cutting face tells that the largest stress-to-strength ratio often appears at the times of 3 to 5 days after the shotcrete lining is cast in place (Celestino & Guimaraes, 1995). Cheng (2007) and Lian & Han (2001) summarized the range of variation of the compressive strength of shotcrete at different ages. The mix design of the shotcrete collected in the statistical data by Cheng & Yang (1998) are as follows: maximum diameter of gravel (20 mm), sand ratio (50%), type and grade of cement (Portland cement of number 425), mixing ratio for cement: sand: gravel: water: accelerants (1:2:2:0.45:0.03), spray process (dry-mix shotcreting), and rebound loss (25%). The shotcrete samples used for the strength tests in the statistical data were prepared in the following way:

1. Spay the mix into a box of 450\*350\*120mm until the box is filled;
2. Cut a specimen of size 100\*100\*100mm out of the sprayed mix;
3. Cure the specimen for 28 days in the temperature of 20±3°C, with a relative humidity of not less than 90%;
4. Measure the compressive strength of the specimen; and
5. Finally, multiply the tested value of the strength by 0.95, which is the dimension-effect reduction factor. In this context, the data collected by Cheng & Yang (1998) were taken into consideration and the statistical parameters of the compressive strength of shotcrete were derived (Table 1).

TABLE 1  
The probability characteristics of the comparative strength of shotcrete at different ages  
[Cheng & Yang, 1998]

Age of shotcrete	5h	10h	3 days	7 days	14 days	28 days	90 days	180 days
Mean (MPa)	3.97	6.56	23.79	27.75	30.36	32.31	34.44	35.17
Coefficient of variation	0.208	0.207	0.129	0.131	0.135	0.140	0.149	0.156
Type of distribution	Normal							

TABLE 2  
Uniaxial compressive strength for three types of shotcrete (MPa) [Oreste, 2003]

Type of shotcrete	Hardening time			
	1-3 hours	3-8 hours	1 day	28 days
Shotcrete without accelerants	0.0	0.2	5.2	41.4
Shotcrete with accelerants (3%)	0.69	5.2	10.3	34.5
Shotcrete with regulated hardening	8.27	10.3	13.8	34.5

As can be seen in Table 1, the coefficient of variation changes with curing time has the largest difference of 0.079; however, considering the scarcity of the data and for the sake of simplicity, it would be reasonable to take one value for each strength grade of the shotcrete throughout the time of curing. The rate of hardening changes for different types of shotcrete. Some typical values of the uniaxial compressive strength of shotcrete in time are illustrated in Table 2 (Oreste, 2003). By virtue of the data presented in Tables 1 and 2, the regulations are pertinent to materials in the Chinese codes.

TABLE 3  
The strength parameters of shotcrete (MPa) (Oreste, 2003)

Parameter	Strength grade of shotcrete				
	C20	C25	C30	C35	C40
Compressive strength $f_{c,0}$	20	25	30	35	40
Tensile strength $f_{t,0}$	1.8	2.0	2.2	2.4	2.6
Elastic modulus $E_0$	21,000	23,000	25,000	27,000	28,000
Coefficient of variation	0.18	0.16	0.14	0.13	0.12

The mechanical parameters of shotcrete can be figured out as shown in Table 3, with all parameters normally distributed. Meanwhile, time constant in Eqs. 7 to 9 describes the speed of hardening. Note that it significantly changes with the types of the shotcrete. Hence, it needs to be determined according to the specific shotcrete used in the project undertaken in the analysis. The typical value of  $\lambda$  ranges from 0.003 to 0.03 (1/h).

As illustrated in Fig. 1, the rise H and the span D of the intrados can be measured directly or be determined through the coordinates of at least three measured points (Points A and B and a midpoint on the intrados). To a specific lining under consideration, how many segments to use and how to divide the lining are determined by user. In general, the measured points can be placed at the crown, the springs, the middles of the sidewalls, the feet, and the midpoint of the invert. The whole lining can be divided into five segments, namely, one segment of arch, two segments of sidewalls, and one segment of invert. Fig. 2 schematically demonstrates the general layout of the measured  $f_{c,t} = f_{c,0}(1 - e^{-\lambda t})$  points and the measured lines which are often incorporated in practice in China. The relevant displacement between the two points can be taken with a convergence meter. When higher accuracy is required, more points and more segments are needed, and more precise instruments should be used in the measurement.

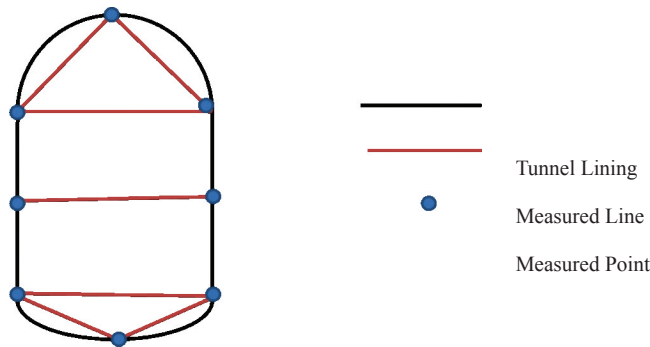


Fig. 2: The arrangement for displacement measurement on tunnel lining

On the basis of the displacements and by means of direct Monte Carlo simulation, the process to compute the reliability index of the lining can be elaborated as follows:

1. For a segment of the lining under analysis at a typical measurement time  $i$ , a set of the values of the basic variables is generated.
2. Compute the arc length  $L_i$  and the radius of curvature  $\rho_i$  of the central axis of the segment at the measurement time,  $i$ .
3. Using Eqs. (2) and (3), the changes in the internal forces from time  $i-1$  to  $i$  are calculated by attaining  $\Delta N_i$  and  $\Delta M_i$ .
4. Taking sum of the internal forces at time  $i-1$  and the changes make the axial force  $N_i$  and the bending moment  $M_i$  at time  $i$  equivalent to  $N_{i-1} + \Delta N_i$  and  $M_{i-1} + \Delta M_i$ , respectively.
5. The value of the performance function  $g$  is evaluated using Eq. (1).
6. Steps 1–5 are repeated by  $m$  times ( $m$  should usually range from 50,000 to 100,000 times of simulation so as to meet the precision requirement in engineering practice), and the number of failure  $n$ , i.e. the occurrence where  $g < 0$  is calculated.
7. The failure probability  $P_f (=n/m)$  and reliability index  $\beta (= \Phi^{-1}(1 - p_f))$  are reckoned to be corresponding to the segment. Here,  $\Phi^{-1}$  stands for the inverse of the standard normal distribution function.
8. Steps 1–7 are performed over all the segments at the cross section of tunnel lining.
9. The smallest reliability index among all the segments is picked to represent the reliability of the shotcrete lining at the typical measurement time,  $i$ .

### CONCLUSION AND REMARKS

This review paper proposes a displacement-based method which can be used to evaluate the reliability of shotcrete lining in tunnel construction. The contents of this work consist of the establishment of the performance function, the investigation of statistical characteristics of basic random variables, and the development of a computer programme and two case studies. The proposed method is applicable to different construction methods such as full face method, full arch method, bench method, and pocket method. Meanwhile, the method relies only upon the displacements occurred of the lining. The method is suitable for safety control and observational design of underground tunnels with shotcrete lining. Reinforced shotcrete is widely used nowadays and it should therefore be studied in future approaches. Deformation resulting from shrinkage, temperature, and creep (Hellmich *et al.*, 2000) needs to be analyzed. More work could be done in generating the method beyond the tunnels to other underground work.



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