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Development of a high performance fully automated application system for shotcrete

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ABSTRACT: Optimized shotcrete application techniques are required to guarantee the life-cycle-behavior of shotcrete shells. Today any spraying is done by hand or by manipulator causing heterogeneities while building up the shotcrete layers. With the automation of the shotcrete application, an important contribution to improve performance and quality may be achieved, while the over-all-costs of rock support by shotcrete may be reduced at the same time. With the development of the fully automated application system for shotcrete, the user will have a very effective tool at his disposal to spray concrete shells with a defined constant layer thickness or to provide the designed tunnel profile. With the new robot the user may choose from three different modes: manual spraying, semi automated and fully automated spraying. Especially the fully automated mode facilitates higher performance with less danger to the workman's health. The quality control is inherent in the application process in regard to layer thickness, compaction, homogeneity, evenness and rebound.

1 INTRODUCTION

Developments in the material technologies have enlarged the range of possible operation of shotcrete. Manipulators and shotcreting machines make high theoretical conveying capacities possible. To improve the over-all-economic-performance, the shotcrete application has now to be improved to enhance steady quality, to reduce rebound, and to improve work hygiene. To achieve these goals a fully automated shotcrete robot was developed at the Swiss Federal Institute of Technology, Zurich. The computer controlled automation system consists of the mechanical process control, the application process control and the application systematic.

2 STATE OF THE ART

2.1 *Spraying by hand*

Shotcrete is in many cases still applied by nozzle operators wielding tube and nozzle. The strain on the workmen limits the quantity of concrete that can be handled. The technique of application has to be trained and needs a lot of experience. The work demands high concentration even from experienced nozzle operators. To get an optimum of quality and a minimum of rebound the nozzle operator has to keep the right distance from, and angle, to the rock surface. In large tunneling sections the nozzle operator must apply the shotcrete from a lifting platform to maintain the optimum position of spraying. The experience on the sites shows that, due to human influence, it is not possible to keep all important application parameter in the best possible combination, especially not in large tunnel sections.

2.2 *Spraying by manipulator*

Performance can be improved by using a manipulator (Fig. 1). Because the strain on the workmen does not

Figure 1. MEYCO Robojet manipulator.

limit the spraying capacity, it may be much improved by using a shotcreting machine with larger capacity and a larger conveyor hose which additionally reduces the pulsation effects and thus improves the surface uniformity of applied shotcrete.

The workman steers the different joints with several joysticks to let the nozzle do the movements. The operation of the joints makes it difficult to keep the nozzle perpendicular to the surface and in the recommended distance. Even with a remote control it is still difficult to hold the quality on a steady level due to the poor visibility caused by the dust of spraying, the too large distance of the nozzle operators to the spray jet as well as the unfavorable angle of sight (EFNARC 1997).

3 AUTOMATED APPLICATION SYSTEM

3.1 *Robot system*

To improve the shotcrete quality and to simplify the application technique a robot was developed on the mechanical basic concept of the MEYCO Robojet manipulator (Meierhofer 1993).

The spraying robot is mounted on a vehicle that is not moving during the spraying process. The location of the nozzle is therefore always described with reference to the vehicle. The robot consists of the nozzle system (joints 7 and 8), the spraying-arm with boom (joints 1, 2, 3, 4 and 5) and lance (joint 6), a laser scanner, the remote control and the sensors and actors that are connected to the computer.

3.2 *Mechanical process control*

The electro-hydraulic spraying-arm owns eight degrees of freedom (Fig. 2). All joints are fitted with robust sensors, whereof six are working on angular and two on linear (joints 2 and 5) measuring principle, that detect the position of each joint to the next one simultaneously. The movements are controlled with standard control valves that are equipped with emergency manual control in case of break down.

In addition to the eight joints one joint is used for a rotational motion of the nozzle tip (opening angle $\varphi_{Rot} = 4°$) for a better distribution of the sprayed concrete. It has no effect on the kinematical model of the boom.

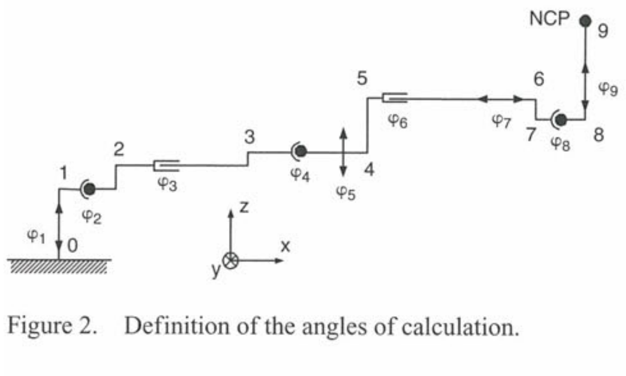

Figure 2. Definition of the angles of calculation.

The vector φ is the joint vector that defines the workspace of the robot, the transversal and rotational vectors at the joints involved in the calculation are:

$$\varphi^T = [\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5, \varphi_6, \varphi_7, \varphi_8]^T$$

The task requires the control of five degrees of freedom of the spraying robot, i.e. the position of the nozzle center point NCP (x, y, z) and 2 angles for the orientation of the nozzle (φ_7, φ_8). To solve the problem of the redundancy 3 constraints are required to link the supernumerary degrees of freedom:

$$\varphi_5 = -\frac{\varphi_1}{3}, \quad \varphi_4 = \frac{1+\varphi_2}{6}, \quad \varphi_3 = \frac{1.85}{3} \cdot \varphi_6$$

The first condition limits the angle at the nozzle so that the perpendicularity of the nozzle to the rock surface is possible at any time. The second condition rules out the possibility of a collision of part 3 and part 6 (Fig. 2) and the third condition optimizes the workspace of the robot.

The computing is based on the inverse kinematic principle which means that for a given movement of the nozzle, a pattern of motion for each individual joint is computed by the mechanical process control. Due to the complicated kinematical structure no closed-form solution for the inverse kinematical model exists. The joint angles are thus calculated numerically with the Newton-Raphson method.

The nozzle operator uses a remote control with a 6D-joystick (Fig. 3), to steer directly the movement of the nozzle, due to the mechanical process control. The 6D-joystick is a large handle with integrated "dead man switch" and guarantees the water- and dust-resistance. The heart of the 6D-joystick is a modified piece of

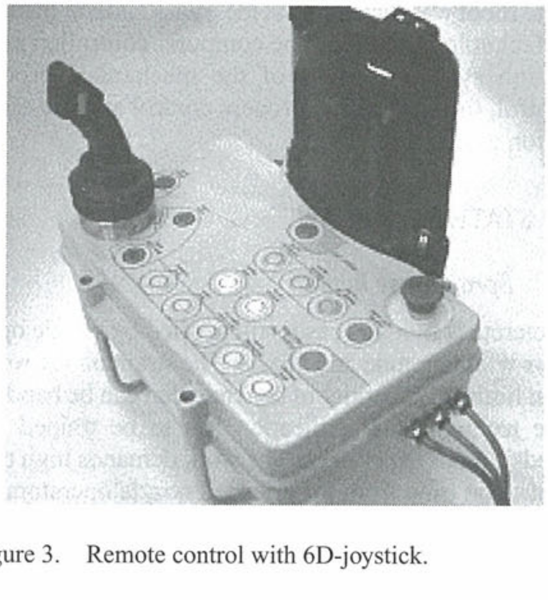

Figure 3. Remote control with 6D-joystick.

equipment that is used as a standard in industrial robotics (Tschumi 1998, Tschumi 1999).

3.3 *Application modes*

3.3.1 *Manual spraying*

The nozzle operator uses the robot as a manipulator to apply shotcrete manually. The application is not supported by the application process control but the movements of the manipulator (boom, lance and nozzle) are controlled by the mechanical control system. After the machine having been positioned, the user is operating the application with the 6D-joystick. He does not have to take care of the individual boom joints but guides only the movement of the nozzle (Fig. 4). With the 6D-joystick are steered:

- Angle of the nozzle to the rock surface
- Path line and velocity of the nozzle v_n
- Distance d_{vp} from the nozzle tip to the tunnel wall.

This mode is thought for irregular conditions where a description of every movement is too difficult to be implemented into an operational program due to its complexity or for economical reasons. Such conditions could be as typical: Irregular local over profile, local covering of drainage half shells and anchor plates or filling of holes caused by rock fall.

3.3.2 *Semi automated spraying*

The user has the freedom to choose the path line; all other process functions of the application are controlled by the application process control and the internal mechanical process control. Contrary to the manual application mode the application process control generates out of the laser controlled measurements a virtual congruent plane to the scanned wall surface. On this plane, the nozzle movement is computer controlled in regard to the wall distance d_{vp} as well as to the perpendicularity of the nozzle to the scanned wall surface. The path of motion of the nozzle has to be manually controlled via 6D-joystick and the spraying distance d_{vp} (distance virtual plane to the rock surface) has to be specified by the nozzle operator (Fig. 5). With the 6D-joystick are steered:

- Path line of the nozzle on the virtual plane
- Velocity of the nozzle v_n.

The semi automated mode avoids increasing rebound particularly in ranges which are badly visible or over head far away from the user due to optimized nozzle control in respect to the wall surface. The semi automated mode is an optional mode which can be used in areas where neither the manual application nor the fully automated modes are economically or technically useful.

3.3.3 *Fully automated spraying*

In comparison with the other two modes, the system has to take over the nozzle operator's experience and supervision functions with the resulting actions. The robot assumes the full control of the shotcrete application process. The measurement is effected in the same way as in the semi automated mode by defining the points from where the automated spraying starts and where it ends. Depending on the input given by the user (spraying distance d_{vp}, layer thickness, conveying capacity) the application process control program does the path planning for the nozzle and drives the nozzle automatically along these path lines, with the required velocity and in the according path line distance d to get the required layers, keeping the nozzle always perpendicular to the surface (Fig. 6). The 6D-joystick is locked, but for safety reasons the user still has to press the "dead man switch".

3.4 *Profile measurement*

Except when using the manual mode, the rock section under consideration has to be measured, but due to the spraying dust any measurement has to be executed before starting the spraying process. The measuring device is located at the head of the lance of the manipulator (in-between joint 6 and joint 7). Thus the range of

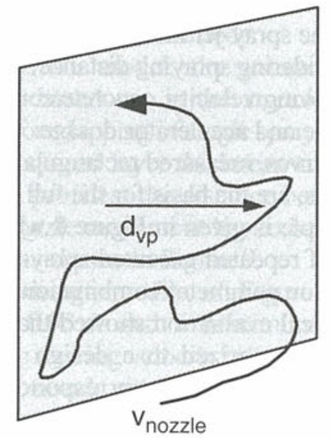

Figure 4. Manual spraying mode.

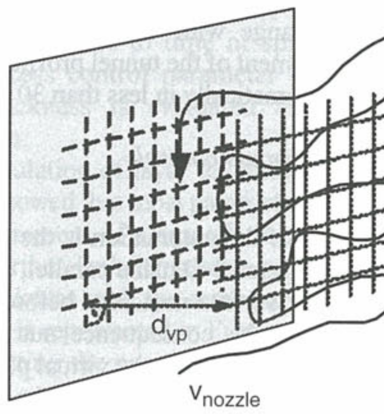

Figure 5. Semi automated mode.

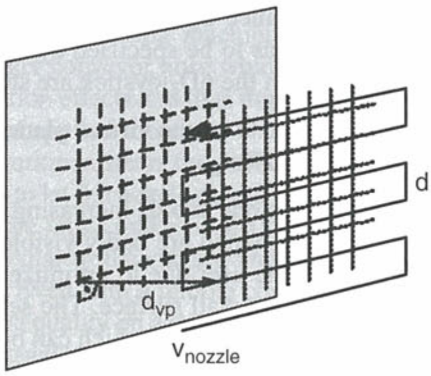

Figure 6. Fully automated spraying.

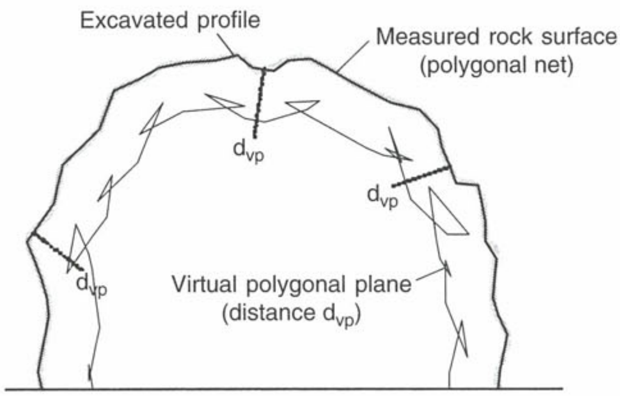

Figure 7. Geometrical place of the nozzle movement.

measurement along the tunnel axis is limited to 3.00 m due to the mechanical structure of boom and lance. The measurement of the tunnel profile is done by a laser measurement system, scanning the tunnel profile in a section of 180 degrees. The measuring principle is a reflector-less transit-time measurement in the infrared range. The user just has to position the lance that the distance laser device – rock surface is approximately the same over the whole tunnel profile (elimination of systematic measuring deviation) and to mark the required spraying range with 4 points by the laser device. The measurement of the tunnel profile is subsequently effected automatically in less than 30 seconds.

3.5 *Application process control*

3.5.1 *Principle*

The basic principle of the automation is the computation of a virtual polygonal 3-D plane parallel, in the distance d_{vp}, to the rock surface measured before (Fig. 7). The nozzle tip is in the consequence automatically guided in and perpendicularly to the virtual plane.

Depending on the chosen mode for the spraying process some parameters have to be given to the system as manual input by touch screen. The specified functions are taken over by the application process control while reducing the nozzle operator's freedom of action: full robot control in the fully automated mode, no application process control in the manual mode (Honegger 1996). The unspecified functions are steered manually by the 6D-joystick that enables a user friendly handling.

3.5.2 *Design of the system intelligence*

If the knowledge of the independent relations of some spraying parameters was sufficient for spraying by hand or manipulator, it is not for spraying fully automated by the robot. The different influences have to be quantified and valued to be put into relation. All these dependent and independent factors have to be linked in the application process program (application process control). Important for the research is the adaptability of any experiments to site conditions because only this demand makes sure that the results are useful to be implemented into the robot application system. Because so many facts can't be influenced on site the data of the experiments shall not be taken to the last two digits after the decimal point. Much more important is the consideration of the interaction of the material and the application parameters.

The investigation of the meander-wise path planning of the nozzle moving turned out that the orientation (horizontal, vertical or any other orientation in between) of the path lines did not influence the concrete quality in regard to homogeneity and compressive strength. The rebound of the applied shotcrete did not vary significantly as well (Guthoff 1991). But to prevent the sagging of the layer-wise applied shotcrete the application has to be carried out from the bottom to the top (EFNARC 1997).

The path planning (vertical or horizontal) is thereby technically determined by the kinematics of the boom and the lance. Because of the orientation of the lance the application in horizontal meander-wise path lines is predominant.

The first step of the development of the application process control was to quantify the distribution of the shotcrete by the spray-jet in one layer along a stretched path line, considering spraying distance, nozzle rotation and nozzle moving velocity, concrete conveying capacity, air pressure and accelerator dosage. The quantified distribution curves, measured rectangular to the path of the spray-strips, are the basis for the full range application. An example is given in Figure 8 where the measured graphs of repeated executed spray-strips with the same application parameter combination are arranged.

The statistical evaluation showed that the distribution curves, summarized to a design profile (mean of graphs of distribution), correspond to the same entirety what means that the design profiles, gained through repeated execution of the experiments, may be compared. Further are the standard deviations

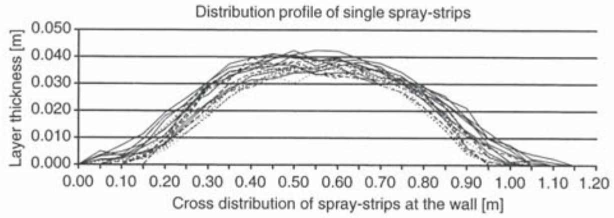

Figure 8. Shotcrete cross-distribution, sprayed in a single strip.

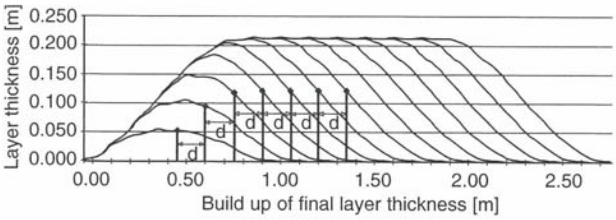

Figure 9. Structure of final layer thickness.

coincidentally. The path of nozzle movement may therefore be developed out of the design profiles.

The maximal design profile thickness that may be achieved vary between 0.02 and 0.07 m depending on the application parameter combination (spaying distance 1.50 or 2.00 m, nozzle moving velocity of 10, 15 and 20 cm/s and nozzle rotation velocity of 1 or 2 RPS) and the effective concrete conveying capacity of 9.5, 12.5 or 15.0 m^3/h (Wijnhoff et al. 1999). Different to the spraying by hand or by manipulator only some application system adjustments can be done while spraying automatically. The reason is that once having left the finished part of the spraying range, which can not be reached by the spray jet in the same passage of spraying any more, the evenness of the sprayed surface has to be final. Therefore the evenness of the shotcrete strips along the stretched path line has to be high; otherwise the requirements of automated shotcrete application are not fulfilled.

The application model, the automated shotcrete application is based on, is the stretched horizontal meander wise overlapping of single spray-strips. Dependent on the required layer thickness and the sprayed layers (design profiles) the distance between the path lines of the nozzle movement has to be calculated by an algorithm as shown in Figure 9.

The basic design profile of Figure 9 i.e. has an extension of 0.95 m and a maximum thickness of 0.05 m (nozzle moving velocity: 10 cm/s, spraying distance: 2.00 m, nozzle rotation velocity: 1 RPS, effective concrete conveying capacity: 12.5 m^3/h). With a spraying path line distance of $d = 0.15$ m, a theoretical total lining thickness of 0.22 m is achieved.

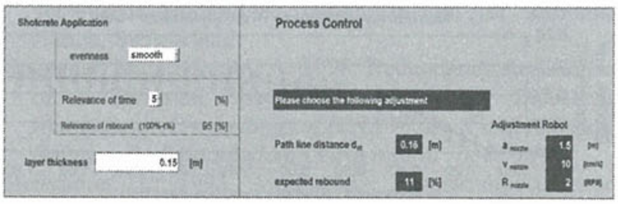

Figure 10. Input mask of the application process control.

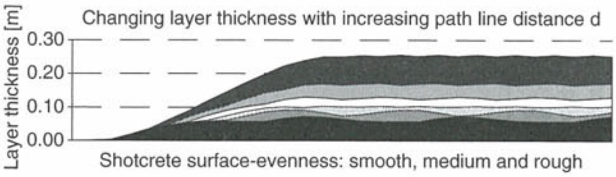

Figure 11. Evenness of shotcrete layers.

Table 1. Proposition of application parameter combination.

concrete conveying capacity [m3/h]				Shotcrete layer [cm]	Spraying distance [m]		nozzle moving velocity [cm/s]		nozzle rotation velocity [RPS]		path line distance [m]
15.0	12.5	9.5		l	d_{vp}		v_N		R_N		d
				5							0.26
		1b33		6	2.00		15		1		0.22
				7							0.19
				8							0.28
				9							0.25
				10							0.22
		1b13		11	2.00		10		1		0.20 / 0.21
				12							0.19 / 0.19
			1c12	13		1.50		10		2	0.17 / 0.18
				14							0.16 / 0.17
				15							0.15 / 0.15
				16							0.24 / 0.19
				17							0.22 / 0.18
3b13	2b13			18	2.00		10		1		0.21 / 0.17
				19							0.20 / 0.16
				20							0.19 / 0.15
				21							0.18 / 0.14

3.5.3 *Simulation of shotcreting*

The experimental data (design profiles, rebound, application parameters, water permeability, compressive strength, air pressure and concrete characteristics) are summarized in a data base. The path line distance is assigned according to the required layer thickness. Specifying the evenness of the surface to be sprayed: smooth, medium or rough, and classifying the relevance of rebound to time of spraying (Fig. 10) the best process control parameter set for the required layer thickness is evaluated automatically by an algorithm.

A simulation of layer thicknesses between 0.05 an 0.25 m showed that most parameter combination fit not the requirement of a smooth surface of the shotcrete shell. Further isn't it possible to spray any shotcrete layer thickness with the same parameter combination. This fact is represented in Figure 11.

Extracting the parameter combinations that fulfill a smooth evenness of the shotcrete layer the following recommendations for shotcrete application may be given (Tab. 1).

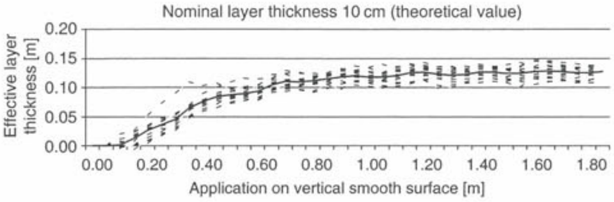

Figure 12. Experimental layer thickness.

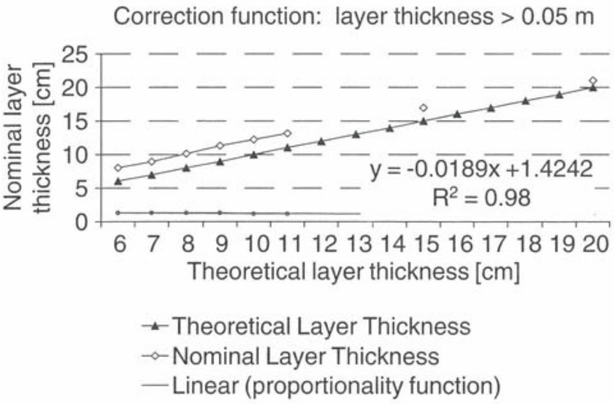

Figure 13. Correction function.

3.5.4 *Improvement of the theoretical model*

Due to the overlapping of the different spray-strips to achieve the theoretical layer thickness the rebound is decreasing and therefore the design profile enlarged. The value of increase is proportional to the gradient of the design profile. This effect was theoretically calculated to about 0.002 m for the design profiles. The quantified increase of 0.001 to 0.003 m fits well to the assumption and is reverse proportional to the thickness of the design profile.

Besides that the accuracy of the movements of the spraying-arm causes an additional uncertainty about the effective shotcrete layer (Fig. 12).

The difference between the theoretically calculated and the effective applied layer thickness depends therefore on rebound and accuracy. These two influences have to be considered and compensated by a correction function (Fig. 13):

- $y = -0.1357x + 1.7286$ ($R^2 = 0.93$) for layer thickness up to 0.05 m and
- $y = 1.3298e^{-0.016x}$ ($R^2 = 0.98$) for layer thickness above 0.05 m.

3.5.5 *Verification on site*

Considering the correction functions the transition from laboratory experimentation to application on site was achieved. The shotcrete application was carried out on pre-sprayed rock and on blasted rock, both washed with water before, with an accelerator dosage of 4, 6 and 8%.

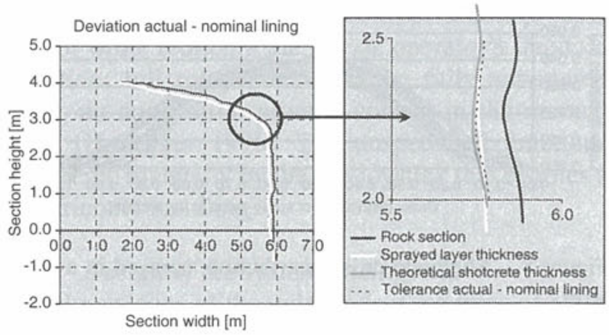

Figure 14. Shotcrete application in blasted tunnel section.

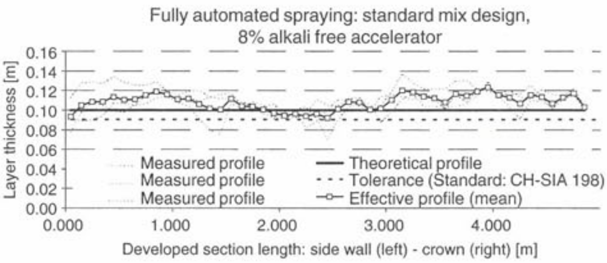

Figure 15. Layer control on site.

That for any application the excavation line is evened out by the shotcreting (Fig. 14), that holes are partially filled while peaks are covered less (Teichert 1991) was confirmed by the fully automated shotcrete application.

In Figure 15 the developed length, from the side wall to the crown is shown for a required layer thickness (theoretical profile) of 0.10 m. According to (SIA 1993) the tolerances of excavation support for shotcrete shells less than or equal to 15 cm is minus 0.01 m. With the simulated and corrected parameter combination the fully automated shotcrete application on a blasted rock surface reaches very well the required shotcrete lining of 0.10 m and ensures that the minimal layer thickness is reached. The layer thickness is importantly more exact than applying shotcrete manually or by manipulator.

4 CONCLUSION

With the development of the "Fully Automated Application System for Shotcrete", companies will have a very effective tool to spray concrete shells as primary rock support or as final lining at their disposal. The application system offers three different modes: manual, semi automated and fully automated shotcrete application. Especially the fully automated mode facilitates higher performance with improved work hygiene. The quality control is inherent in the application process to guarantee the life-cycle-behavior of the tunnel shells in regard to layer thickness, compaction, and homogeneity. The time consuming profile and quality control, due to the optimized combination of the important application parameters with regard to performance, rebound, quality and time, the over-all-costs, may be reduced.

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