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Muck discharge by the screw conveyor of an EPB Tunnel Boring Machine

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ABSTRACT: A mathematical model for muck discharge by the screw conveyor of an Earth Pressure Balance (EPB) Tunnel Boring Machine is presented. The muck is modelled as a homogeneous plastic paste. The model considers momentum balances and kinematic conditions of muck flowing between the rotating screw and the barrel.

The mathematical model has been validated against laboratory scale experiments and field measurements during the construction of the "Botlek Rail Tunnel". Major differences were found between the functioning of the screw conveyor in the laboratory tests and in the field. The adhesive properties of the muck are an important factor for controllability of muck flow rate and confinement pressure by the screw.

1 INTRODUCTION

Earth Pressure Balanced (EPB) shields are used on a regular basis in soft soil shield tunnelling and have proven their capabilities. Additives are necessary to use these shields in sandy subsoil. Foam has proven to be a successful additive in various projects. However, the governing mechanism that makes foam to a successful additive are not yet clarified, see also Bezuijen (2002).

The double-tube Botlek Rail Tunnel under the River Oude Maas near Rotterdam is the first bored rail tunnel in the Netherlands. An EPB shield tunnel-boring machine was used, see Figure 1. For more detail see Maidl (1999).

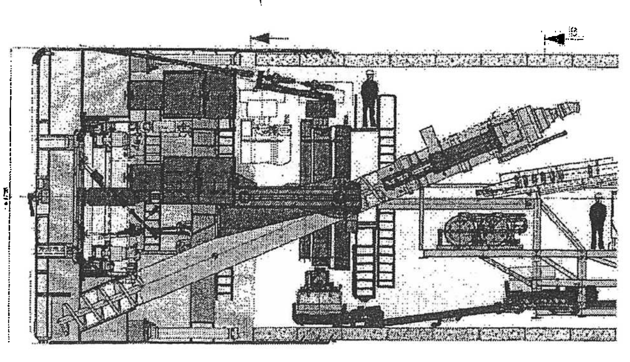

Figure 1. EPB machine Botlek Rail Tunnel.

Soft clayey layers are suitable for EPB shield tunnelling. In EPB tunnelling the soil is excavated under pressurised conditions to balance the tunnel face. In principle water or other substances do not dilute the soil. The earth paste is transferred via a screw conveyor from the pressurised chamber to the rear of the shield.

In the Botlek Rail Tunnel the transport of excavated soil from the working chamber is controlled by a combination of a screw conveyor, a hydraulically operated back gate (when necessary), two bulk pumps (when necessary), a conveyor belt and a hydraulic circuit. In cohesive soils, a pressure difference of some 3 bar can be controlled by the screw conveyor alone, Maidl (1999). In sand-layers the increased water permeability and internal friction will cause serious problems. Intensive soil conditioning with high density slurry or foam is required.

In an EPB tunnel boring machine the screw conveyor has to provide two important functions. First it transports soil out of the excavation chamber while the pressure decreases from the confinement pressure in the excavation chamber to atmospheric pressure at the discharge end of the screw conveyor. And secondly the confinement pressure in the excavation chamber is controlled by the operating conditions of the screw conveyor.

To investigate the mechanisms involved, model tests have been performed. In these tests the relevant parameters were measured (flow rates, pressures, etc.). The set-up of the tests and some results of the measurements have been presented by Bezuijen and Schaminée (2001).

A mathematical model for the muck discharge by a screw conveyor is given in Section 2. The model is used for an analysis of the model tests and the screw conveyor in the TBM of the "Botlek Rail Tunnel". The results are given in Section 3 and Section 4 respectively.

2 MATHEMATICAL MODEL SCREW CONVEYOR

The model was set up to relate muck discharge and confinement pressure with the rheological properties of the muck and the operational conditions of the screw conveyor. It is intended as a tool for prediction and analysis. The basic ingredients of the mathematical model are:

Kinematic conditions: flow rate of the muck, angular velocity of the muck, angular velocity of the screw, continuity.

Forces: angular momentum balance and longitudinal momentum balance. In these the shear stresses are assumed to be uniformly distributed over the screw, over the root of the screw and over the barrel. The direction of shear stresses over the barrel is variable, depending on operational conditions of the screw conveyor. The pressure difference over the blade is accounted for.

The muck is modelled as a homogenous plastic one-phase material. A definition sketch is given in Figure 2.

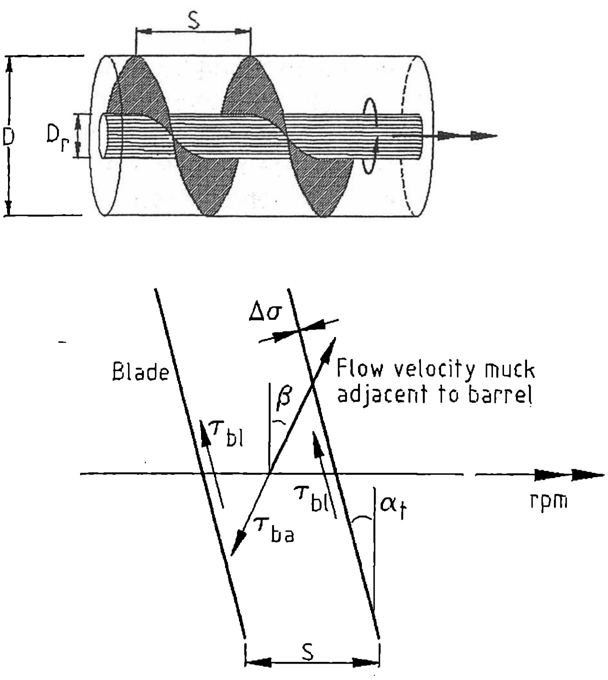

Figure 2. Definition sketch mathematical model screw conveyor, relating geometry, operational conditions and stresses.

The geometry of the screw at the edge of the blade is given by, see Figure 2:

$$\tan\alpha_t = \frac{S}{\pi D} \tag{1}$$

with: S = pitch, D = diameter barrel, α_t = blade angle at the edge of the blade.

The characteristic flow rate of the screw is:

$$Q_{straight} = \frac{rpm}{60} S \frac{\pi}{4}(D^2 - D_r^2) \tag{2}$$

with: rpm = rotational frequency of screw conveyor [rotations/min], $Q_{straight}$ = flow rate when the muck moves in a straight line (e.q. without axial rotation). D_r = diameter of the root of the screw.

From kinematic conditions:

$$\tan\beta = \frac{\tan\alpha_t}{Q_{straight}/Q - 1} \tag{3}$$

with: Q = flow rate of the muck, β = direction of the flow adjacent to the barrel.

Muck rotation is in the same direction as the rotation of the blade for $Q_{straight} > Q$. The muck rotates in opposite direction for $Q_{straight} < Q$. The mathematical expression for the pressure difference over the screw conveyor is (valid for $0 < \beta < 180$ degrees):

$$\Delta p = \frac{4L}{D - \frac{D_r^2}{D}} \left(\begin{array}{l} \frac{1}{\pi}(1 - \frac{D_r}{D} + \frac{1-(D_r/D)^3}{3\tan^2\alpha_t})\tau_{bl} \\ + \frac{\tan\beta}{|\tan\beta|} \frac{\tan\alpha_t \tan\beta - 1}{\tan\alpha_t \sqrt{\tan^2\beta + 1}} \tau_{ba} \\ + \frac{D_r}{D}\sqrt{1 + (\frac{\pi D_r}{S})^2}\,\tau_{rt} \end{array} \right) \tag{4}$$

with: L = length screw conveyor, τ_{bl} = shear stress on the blade, τ_{ba} = shear stress on the barrel, τ_{rt} = shear stress on the root of the screw.

The pressure difference over the screw conveyor is a function of the flow rate of the muck (Q), the rotational velocity of the screw and the friction with steel surfaces. The direction of the flow ($\tan\beta$) is calculated by Equation (2) and Equation (3). Next ($\tan\beta$) is substituted in Equation (3) to calculate the pressure difference. In Figure 3a the dimensionless pressure difference over the screw conveyor is given as a function of the dimensionless flow rate $Q/Q_{straight}$, under the assumption that the friction at the blade is equal to the friction at the barrel and at the root.

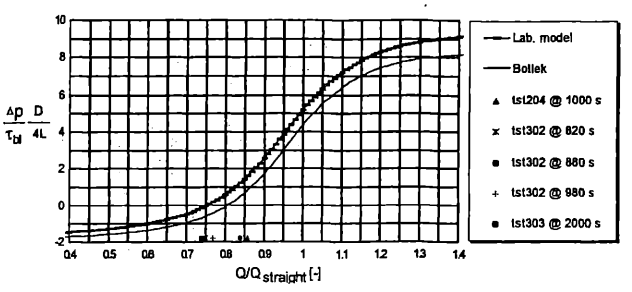

Figure 3a. Mathematical model screw conveyor (geometry model tests: S/D = 0.70 and D_r/D = 0.45, Botlek Rail Tunnel: S/D = 0.63 and D_r/D = 0.22). Dimensionless flow rates in model tests are indicated on the ordinate.

Two curves are shown: one for the geometry of the screw conveyor in the model tests, and one for the Botlek Rail Tunnel. The graph shows that theoretically different operational transport modes are possible: passive confinement of pressurised muck in the excavation chamber for $Q/Q_{straight}$ > 0.75 (in the laboratory model), or active extraction of muck from the excavation chamber for $Q/Q_{straight}$ < 0.75. The later is referred to as 'pumping action'. The calculated pressure difference is exclusive the static pressure. Some operational conditions, in which high-pressure differences have been measured, are displayed on the ordinate of the graph.

In practise a screw conveyor in a TBM might be equipped with additional foam injection ports, see for instance Maidl (1999). This additional foam might lower the friction with the barrel. The functioning of the screw conveyor under such a condition, according to Equation (4), is shown in Figure 3b. For $Q/Q_{straight}$ < 0.96 the pressure difference between the entry and the exit of the screw conveyor increases.

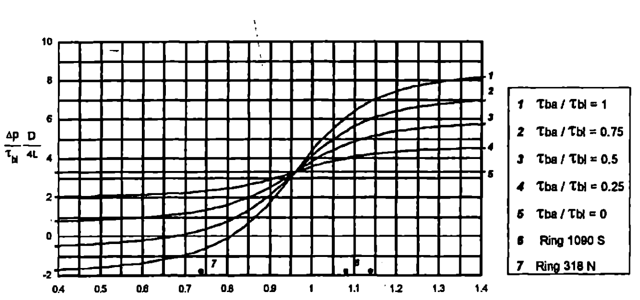

Figure 3b. Mathematical model screw conveyor: Botlek, variation of ratio τ_{ba}/τ_{bl}. Dimensionless flow rates for two situations being analysed are indicated on the ordinate.

A comparable situation results when a velocity dependent Bingham rheological flow model models the consistency of the muck. Than, for $Q/Q_{straight}$ > 0.5, the velocity of the muck with respect to the blade is larger than with respect to the barrel. Consequently the shear stress on the blade is larger than on the barrel. The result is then comparable to Figure 3b.

3 LABORATORY EXPERIMENTS

Saturated sand was mixed with foam and the sand-water-foam mixture was removed with a screw conveyor, see Bezuijen and Schaminée (2001). The drilling direction, compared to field conditions, was changed from horizontal to vertical. The test set-up is shown in Figure 4. The internal diameter of the excavation chamber is 0.6 m. Not shown are a foam generator and a foam container from which the foam was released into the model container. The pressure in the excavation chamber was about 100 kPa. The specifications of the screw conveyor are: length barrel L = 1.2 m, diameter barrel D = 107 mm, diameter root D_r = 48 mm, pitch screw S = 75 mm, thickness blade ~ 2 mm. Substitution of these specifications in Equation (2) gives: $Q_{straight} = 0.031 * rpm$ [m^3/h]. Some selected conditions where the screw conveyor controlled the discharge of muck are listed in Table 1.

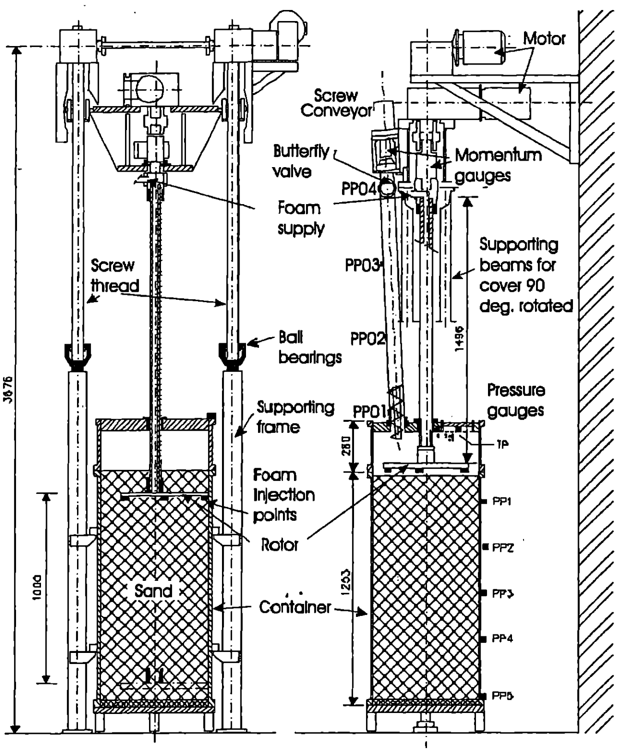

Figure 4. Set-up model test.

Some examples of the measured pressure distribution along the screw conveyor are shown in Figure 5.

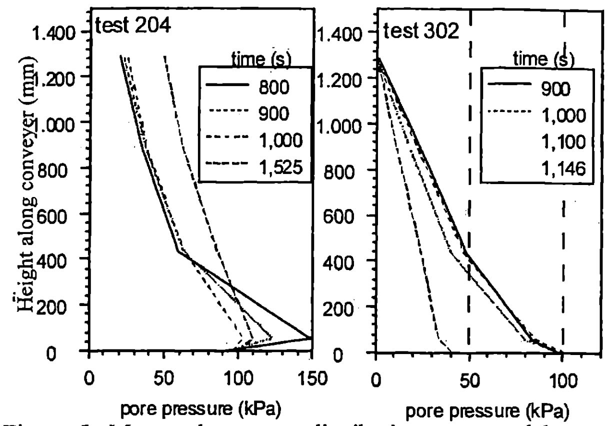

Figure 5. Measured pressure distribution over model screw conveyor.

Table 1. Test conditions of the screw conveyor in model tests (at mean pressure in screw conveyor).

parameter	test 204	test 302	tests 303
d_{50} sand [um]	250	135	250
Sand porosity	0.35	0.40	0.36
Drill vel. [mm/s]	0.49	0.73, 0.82, 0.96	0.31
FIR [-]	0.38	0.41	0.39
FER [-]	1:14.9	1:14.6	1:15.5
c_{sand} [v%]	48	45	50
c_{water} [v%]	13	14	9
c_{air} [v%]	39	41	41
rpm	24	32.5, 37, 43	18
Flow rate Q [m^3/h]	0.63	0.90, 1.0, 1.24	0.41
Pressure drop [kPa]	90	100, 100, 100	65
$Q/Q_{straight}$	0.86	0.89, 0.88, 0.93	0.84

The operational conditions listed in Table 2 relate to t = 1000 in test 204, t = 820, 880 and 980 in test 302 and t = 2000 in test 303. The measured pressure difference includes 15 kPa static pressure.

The dimensionless muck flow rate $Q/Q_{straight}$ for the conditions above is displayed on the ordinate of Figure 3a. According to this model the operating conditions are in the region where the screw conveyor provides a positive pressure difference ($Q/Q_{straight} > 0.75$). This is in agreement with the measurements. The shear stress is back calculated from the dimensionless pressure difference read from the abscess of Figure 3a. The results are summarised in Table 2.

Table 2. Functioning screw conveyor in laboratory tests.

model test	$Q/Q_{straight}$	$\Delta p/\tau$ D/4L math. model.	τ [Pa] back calculated
test 204	0.86	1.6	1040
test 302	0.89	2.0	950
test 302	0.88	2.3	830
test 302	0.93	3.3	580
test 303	0.84	1.2	910

The results compare with vane tests at a mixture porosity of $n = 0.52$: $\tau = 1.5$ kPa, see Bezuijen and Schaminée (2001) and Bezuijen *et. al.* (1999).

4 SCREW CONVEYOR IN BOTLEK RAIL TUNNEL

The boring of the two tubes took place in the period 1999-2000. The geology of the subsoil and the main features of the tunnel are summarised by Maidl (1999).

4.1 Properties foamed soil

A number of samples was taken directly from the excavation chamber. The location where the samples were taken is at about half height of the bulk head 3.5 m from the centreline of the TBM. The cohesive properties of the muck were determined by means of a specially designed vane apparatus in the excavation chamber (the measurement took place during placement of lining segments, when the excavation was halted). The vane was located a few decimetres below the location where samples were extracted and at another location about 1 metre aside of the entrance of the screw conveyor.

The porosity of the samples was in the range 0.5 to 0.7, with extremes of 0.46 and 0.72. The volume percentage air in the samples (at ~3 bar in the excavation chamber) was in the range 25 to 35 v%. The measured porosity of the muck was higher than the maximum porosity n_{max} of the sand ($0.44<n_{max}<0.53$). For a homogenous muck there will be no grain contacts and the muck will be workable. Only in one test (Ring 341 North tube), out of a total of five of such tests, the measured porosity of the muck was smaller than n_{max}. The measured internal shear strength of the muck in the excavation chamber was within a range of 5 a 30 kPa.

4.2 Screw conveyor

The screw conveyor of the Botlek Rail Tunnel is shown in Figure 1. Technical specifications are: length barrel L = 16 m, diameter barrel D = 1000 mm, diameter root D_r = 220 mm, pitch screw S = 630 mm, thickness blade ~ 20 mm, max. rpm 22.4, max. flow rate 500 m^3/h. The flow rate of muck transported in a straight line is calculated by: $Q_{straight} = 26.9 * rpm$ [m^3/h]. The screw conveyor is equipped with a number of pressure gauges.

4.3 Analysis of the functioning of the screw conveyor

During the major part of the construction of the tunnel, the pressure drop along the length of the screw conveyor was about 150 kPa. At the same time a pressure drop of about 100 kPa was noticed in front of the screw conveyor. When the flow is regulated by the back gate, the pressure in the back of the screw conveyor is about 100 a 150 kPa. The pressure drop over the screw conveyor includes a static 70 kPa that is attributed to a height difference of 5.5 m.

An example of pressures measured during the excavation and during the positioning of tunnel lining segments is shown in Figure 6.

The pressure distribution over the length of the screw conveyor during the excavation is shown in Figure 7. From Figure 6 it is concluded that during standstill the muck at the entrance to the screw conveyor is compacted, and may balance 1 bar. When the excavation recommences, the situation quickly restores itself to the former situation.

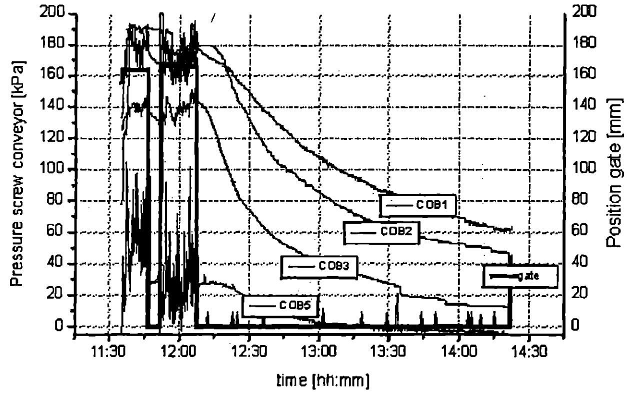

Figure 6. Botlek Rail Tunnel: pressure gauges along the screw conveyor as a function of time: South tube, Ring 1090. For t>12:10 the excavation is halted and tunnelining segments are placed.

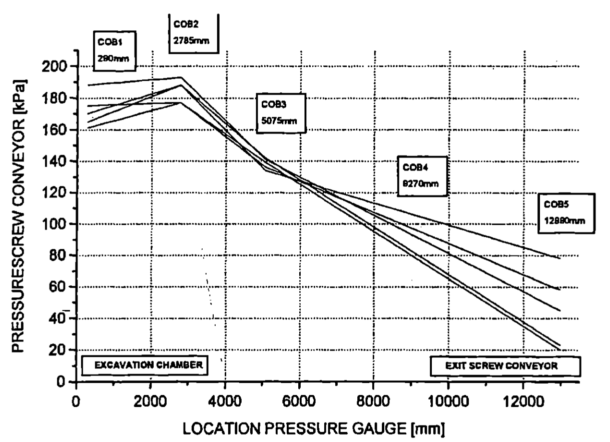

Figure 7. Botlek Rail Tunnel: pressure distribution along screw conveyor during excavation at different time-instances: South tube, Ring 1090.

Two situations where typical high pressure differences were observed over the screw conveyor are discussed: Ring 1090 of the South tube and Ring 318 of the North tube. The average in situ porosity at Ring 1090 South tube was $n = 0.45$, and at Ring 310 of the North tube $n = 0.4$. The consistency of the muck was determined from samples obtained from the excavation chamber (Ring 1090 South and Ring 310 North). The flow rate of muck through the screw conveyor was calculated by two alternative methods: 1) From the in-situ porosity of the soil, the water content of samples and the volumetric air content of samples from the excavation chamber (the ideal gas-law was used to calculate the flow rate at the mean pressure level in the screw conveyor). 2) From the discharge by a slurry circuit that conveyed the soil out of the tunnel and the volume of air in the samples taken from the excavation chamber (also calculated at mean pressure level in the screw conveyor). The latter method is inaccurate at low drill velocities. In Ring 1090 South, foam was injected in the barrel. The operational conditions of the screw conveyor are summarised in Table 3.

Table 3. Operational conditions of the screw conveyor in the Botlek Rail Tunnel (at mean pressure in the screw conveyor).

parameter	Ring 1090 South tube	Ring 318 North tube
d_{50} sand [um]	180	150
Drill vel. [mm/s]	0.96	0.31
c_{sand} [v%]	29	32
c_{water} [v%]	21	16
c_{air} [v%]	50	52
rpm	17.9	7.8
Flow rate Q [m^3/h]	490 (from face) 530 (slurry circ.)	114 (from face)
Pressure drop [kPa]	150	200
$Q/Q_{straight}$	1.06 (from face) 1.14 (slurry circ.)	0.73

The dimensionless muck flow rate $Q/Q_{straight}$ of the conditions above is displayed on the ordinate of Figure 3b. According to the model (in case $\tau_{bl} = \tau_{ba} = \tau_{rt}$) the dimensionless pressure difference for the operating conditions listed in Table 3 are: $\Delta p/\tau\ D/4L = 6$ á 7 for Ring 1090 South, and = -0.8 for Ring 318 North. The back calculated wall shear stresses in Ring 1090 is 220 Pa. For the situation in Ring 318 North the outcome of this model-configuration is contradictory to the measurement.

When alternatively it is assumed that the friction between the muck and the blade is dominating, then the shear stress can be back-calculated from the curve $\tau_{ba}/\tau_{bl} = 0$ in Figure 3b, the result is $\tau = 450$ á 650 Pa.

These back-calculated shear stresses are an order of magnitude smaller than the shear stress measured by the vane tests in the excavation chamber.

5 CONCLUSIONS

Conclusions are:

1) Two rheological properties of the muck have to be discerned: friction with steel surfaces (adhesion) and internal friction (cohesion). The former is relevant to the functioning of the screw conveyor as a flow and pressure regulator. The latter is probably governing the pressure drop that occurs at the entrance of the screw conveyor and the pressure build-up in front of the back gate, when in use. Typical confinement pressures of 3 bar were

balanced. This compares with the situation in Japan, where two-stage screw conveyors are used to deliberately create sand plugs for pressure confinement, Babendererde (1991).

2) We have found major differences between the functioning of the screw conveyor in the laboratory model tests and in the field at the TBM of the Botlek Rail Tunnel. At the TBM, large differences were found between cohesion and adhesion. In the laboratory tests these differences were only about a factor of two. Explanations for differences are:

- The porosity of the muck at Botlek was significantly higher than in the laboratory tests. This could have lead to poor adhesion properties.
- Foam injection in the barrel could have impaired the functioning of the screw conveyor.
- The velocity difference between the blade and the muck is larger than the velocity of the muck with respect to the barrel. If the muck were visco-plastic the friction in the screw channel is the governing factor, as was found at Botlek Rail Tunnel.
- The screw channel might be clogged.

3) The injection of smaller quantities of foam should be considered in future tunnelling projects to produce a muck with a lower porosity than at Botlek. The muck will become more stable and the controllability of the muck flow rate and the confinement pressure are expected to improve. The functioning of the screw conveyor will improve when the adhesive properties are improved. According to the mathematical model, the highest-pressure differences will be attained at slow rotation of the screw.

4) To further improve the control of the muck pressure in the excavation chamber, the attention should be directed towards developing foams and injection recipes that provide higher friction between the muck and steel parts.

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APPENDIX I. NOTATION

D : diameter barrel
D_r : diameter root screw
L : length screw conveyor
n : porosity
Δp : pressure difference over screw conveyor (excl. static)
Q : muck flow rate
$Q_{straight}$: flow rate when muck moves in a straight line
S : pitch screw
α_t : blade angle at edge of blade
β : direction of the flow adjacent to barrel
τ_{ba} : shear stress on barrel
τ_{bl} : shear stress on blade
τ_{rt} : shear stress on the root of the screw