INFLUENCE OF THE RELOCATION BEHAVIOUR OF PEA GRAVEL ON THE DESIGN AND CONSTRUCTION OF SHIELD-TBM DRIVEN TUNNELS

VPLYV PREMIESTNENIA ŠTRKOVITÉHO ZÁSYPU NA NÁVRH A KONŠTRUKCIU ŠTÍTU TBM V TUNELOCH

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ABSTRACT
The quality of the backfill applied at a shield driven tunnels is of significant importance for the stability of the lining. The used material also affects the interaction between support and ground behaviour.
In this research an analytical approach, laboratory tests and numerical simulations investigate the state of the actual bedding situation. The numerical simulation using continuum methods have shown shortcomings. These shortcomings regarding the instability of large strain simulations restrict the possibility to reproduce the relocation of the backfilling material. The performed scaled model tests have shown that the regripping process of a double shielded tunnel boring machine affects the soil failure within the gap. The tests have shown that the current design of the TBM or the segmental lining is in need of improvement when pea gravel is used. Within this research the influence of the uneven distributed pea gravel within the annular gap is discussed. Possible alterations on the design and construction of underground structures are given. Those are categorized into lining design, TBM improvements and numerical pre design.

1 Introduction

When tunnel boring machines (TBM) with a single (SM) or double (DSM) shield are applied, precast lining segments are used as outer or final lining. The diameter of the shield is smaller than the excavation boundary in order to reduce the friction and thus the required thrust force. The thickness of the gap depends on the expected radial convergences and is called steering gap since it influences the minimal curve radius performed by the TBM. Since the lining segments are installed within the protection of the shield the size of the steering gap increases and is hereinafter called annular gap (see Fig. 1).
A DSM consists of two shields connected by telescopic thrust cylinders. The front shield which is connected to the rotating cutterhead covers the main bearing and contains the main working area and the gripper shield which contains the grippers and the auxiliary thrust cylinders. Furthermore, the lining segments are installed forming a closed ring. While the front shield advances using the main thrust cylinders the gripper shield uses either the

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grippers or the auxiliary thrust cylinders pushed against the lining segments to form an abutment. This process allows the DSM to perform advance rates up to 50 m per day installing the excavation support and performing the tunnel advance at the same time. When the Auxiliary thrust cylinders reach their full stroke, the clamping of the grippers is released and the gripper shield is pushed forward one segments width (approx. 2 m).

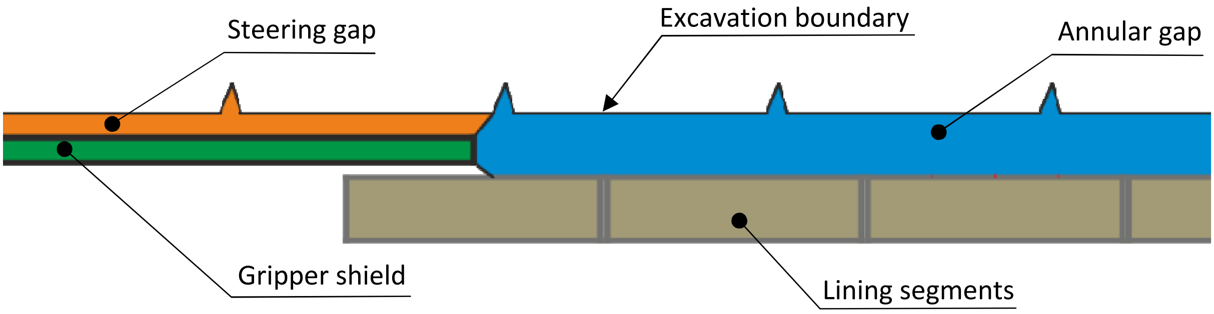

Fig. 1 Schematic view of the excavation boundary and the segmental lining

The support of a shield driven tunnel can be divided into different sections. Within this research, the gripper shield and the segmental lining area are of great importance. The shield section is supposed to protect the working area and the main bearing as well as the thrust cylinders from falling blocks (ÖGG 2013). In hard rock conditions, the shield is not supposed to serve as ground support as too much load causes high thrust forces. The lining segments are installed within the protection of the shield. These segments are usually made of reinforced concrete. However, other applications with non reinforced or fibre-reinforced concrete segments exist (ÖVBB 2012).

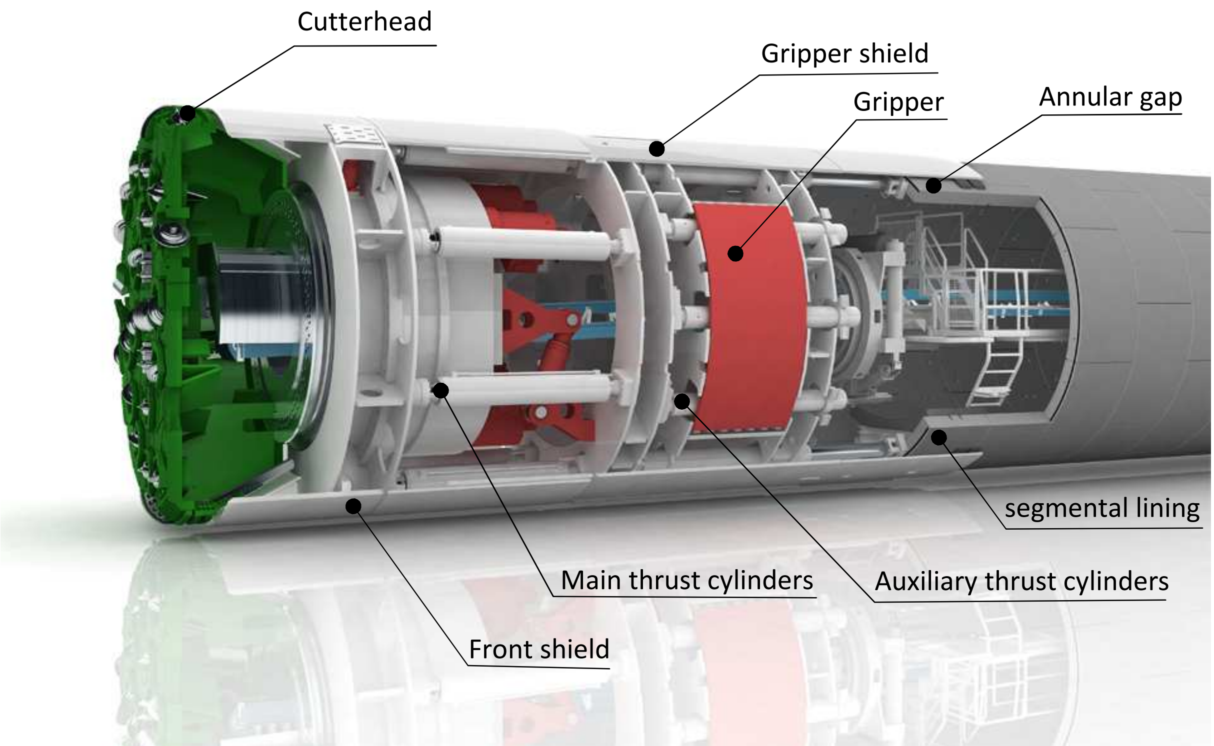

Fig. 2 Shematic view of a DSM

When the new installed ring of segments passes the shield tail, the lining starts to ovalize due to gravitational forces since there is no thorough contact with the excavation boundary. Therefore the gap is usually filled with mortar or pea gravel. In the process of tunneling in hard rock, the annular gap is usually filled with fine grained and closely graded gravel, termed as pea gravel. The backfilling process is conducted as soon as possible after each regripping process. Due to the operational procedure and insufficient space to allow several working steps at the same time, a fully backfilled annular gap might not be established every time. Furthermore, a complete filling of the annular gap up to the crown is difficult but possible. The backfilling material provides the contact between the surrounding rock formation and the lining segments. Therefore, the deflection forces can be transferred between these two elements.

The rapid advance of a DSM requires a permanent backfilling of the annular gap. The regripping process removes the longitudinal abutment of the pea gravel. This leads to a shear failure of the gravel within the annular gap and therefore to a relocation process towards the bottom area and the newly positioned shield tail.

2 Scaled model tests

Within this research scaled model tests have been performed in order to investigate the failure and relocation behaviour of pea gravel within the annular gap. Two different test setups have been executed. Unlike the Coulomb lateral earth pressure theory (Coulomb 1776), these tests also consider the influence of the lateral wall friction, which affects the failing soil block.

For these tests a model scale of 1:20 was used. With an annular gap of about 20 cm and a grain size of 1 cm, this leads to a spacing of 1 cm a grain size of 0.5 mm in the model. For this purpose local river sand sediments were used. To obtain a closely graded material the fraction between 0.4 mm and 0.5 mm was extracted for the tests. The strength parameters and the specific weight are listed in Table 1.

Table 1 Laboratory tests on sand fraction 0.4 – 0.5 mm

Property	Unit	Description	Value
ρ_S	[g/cm³]	Particle density	2.69
φ’	[°]	Effective friction angle	34
c'	[MPa]	Effective cohesion	0

2.1 Test setup

Planar regripping tests were performed, in order to investigate the influence of the lateral wall friction (Henzinger 2015). Within this research the failure mechanism of sand within two acrylic plates, triggering the wall friction and an arching effect was investigated. Within this test series the spacing between the two acrylic plates was increased steadily to evaluate the influence of the gap size to grain size ratio on the angle of failure.

Figure 3 shows the results of the planar soil failure tests. The blue series shows the directly measured failure angle of the soil body. The red series represents the back calculated values from the repose angle using Coulomb’s limit equilibrium theory for the lateral earth pressure. The intersection of both trend lines, which have been extrapolated, indicates the theoretical influence limit of the wall friction at a spacing of 7.8 cm. Therefore, the gap width to grain size ratio results in 15.6 to 19.5 with a grain size of 0.4 to 0.5 mm. With a failure angle of 61.3° at the given spacing of 7.8 cm the friction angle according to Coulomb’s theory is set to 33°, which corresponds to the laboratory test results.

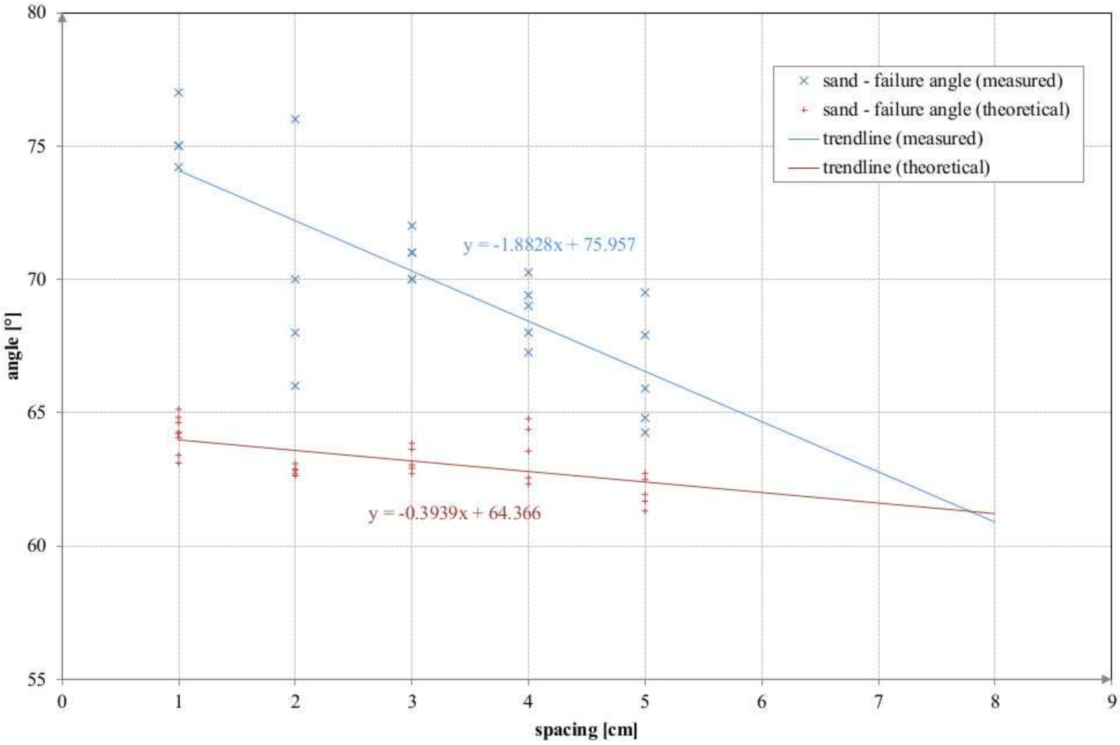

Fig. 3 Influence of the failure angle (Henzinger 2015)

The regripping tests show with the circular models the failure and relocation mechanism within the annular gap. A test setup consisting of two pipes representing the excavation boundary and the segmental lining respectively, has been built. A steel ring represents the DSM shield, which can be shifted using a crank mechanism to simulate the regripping process. Figure 4 shows the test setup.

The failure mechanism was documented using several cameras filming the top, the side and the bottom view. To be able to investigate the deformational behavior during the test videos were taken. Using particle image velocimetry (Thielicke 2014) the failure and deformation process could be located and quantified.

Fig. 4 Setup for the circular regripping test

2.1 Test results

In order to show the full extent of the failure mechanism and the relocation behaviour the steel ring was shifted as long as the sand reached a stable state within the annular gap. Figure 5 shows the final distribution after the shift.

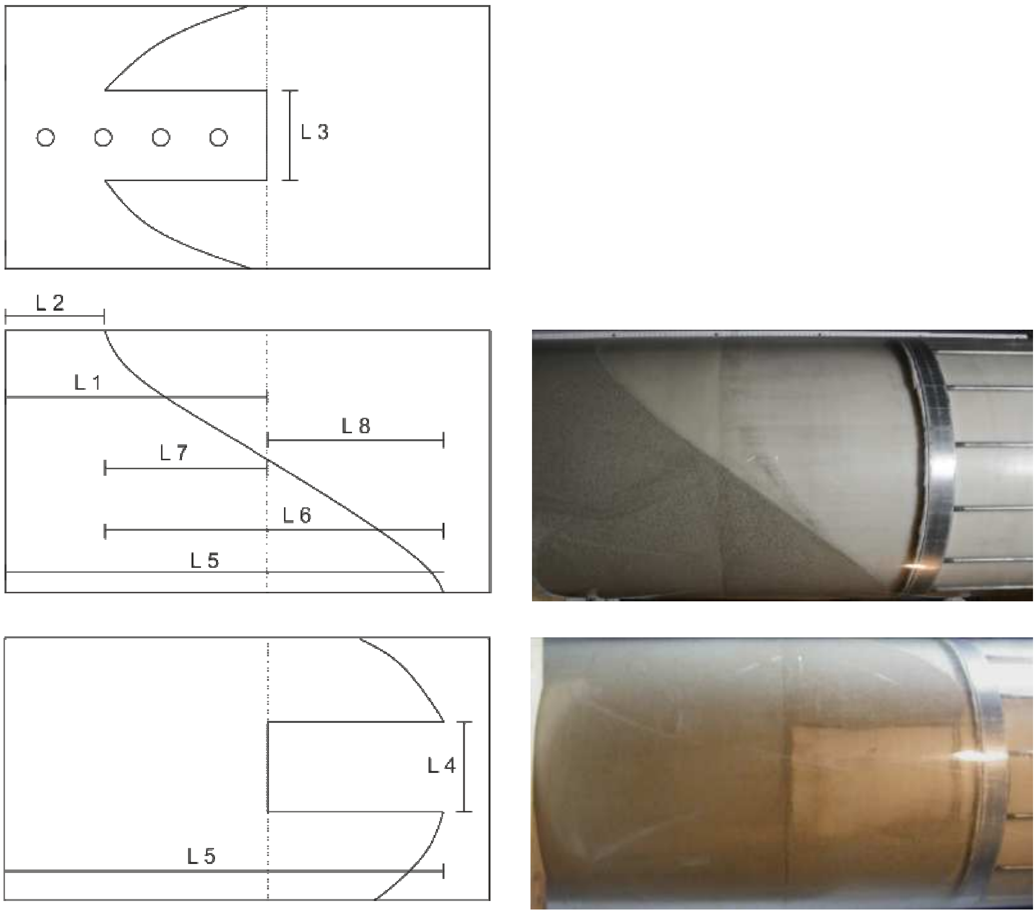

Fig. 5 Sand distribution within the annular gap after the relocation process

The tests show the shape after an extended regripping process. The bottom view shows that the invert segments are not bedded due to the friction between sand and the outer pipe. In addition, the segments at the sidewall are only partially bedded. This leads to a different bedding situation throughout the annular gap dividing the segmental lining into a fully bedded, partially bedded and unbedded area as shown in Figure 6.
State of the art calculation methods for segmental linings include following (Behnen, 2013):

- One dimensional „frame model method“ without ground interaction
- One dimensional „bedded frame model method“ with ground interaction
- Analytical approaches („pane with hole“ (Kirsch 1898))
- Numerical simulations

Especially for the lining pre design the frame model methods have proven useful tools. In the German speaking part of Europe these methods are widely used for the final design to such a degree as the main influencing factors from the ground structure can be included with sufficient accuracy. The shortcomings of this method contain following characteristics (Behnen, 2013):

- Separate determination of rock loads

- Limited consideration of inhomogeneous and anisotropic boundary conditions
- Nonlinear behaviour has to be simplified
- Groundwater conditions have to be evaluated separately
- Pre displacements cannot be considered
- Implementation of excavation steps is not possible
- 3 dimensional investigation of the system behaviour is not possible

The irregular distribution of pea gravel within the annular gap and its influence on the design and construction of underground structures is discussed. The simulation of the filling has been performed using coupling elements connecting the lining and the excavation boundary numerically. Due to the difficult estimation of the input parameters, radial and tangential springs have been introduced for simplified numerical applications or analytical solutions. Both methods do not respect an inhomogeneous distribution of pea gravel within the annular gap.

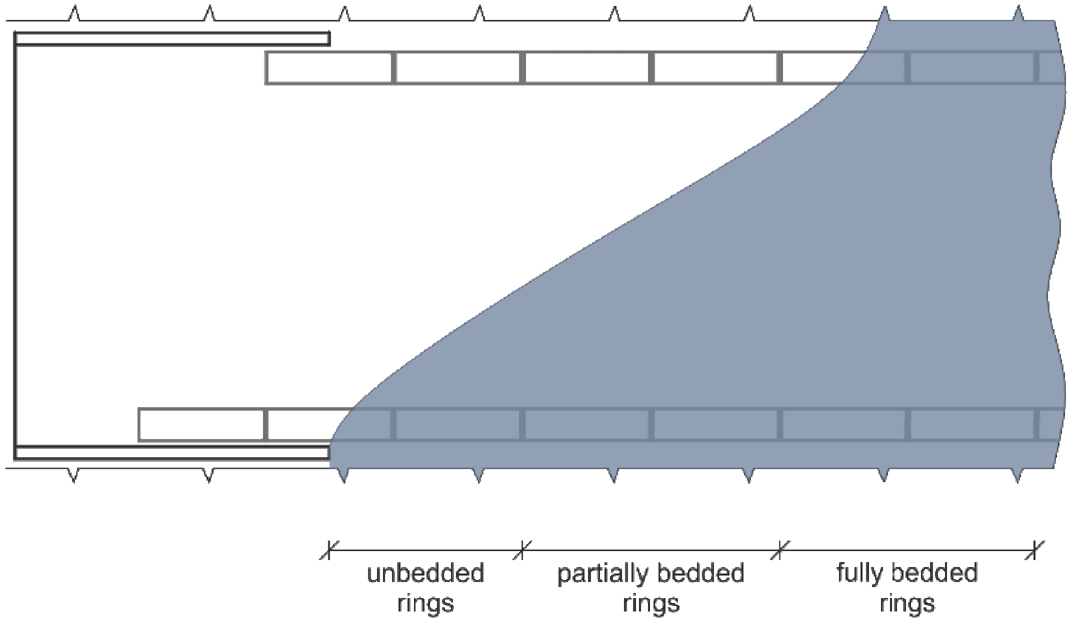

Fig. 6 Distribution of pea gravel creating different bedding situations throughout the annular gap

3 Design improvements

The inhomogeneous distribution of pea gravel within the annular gap affects the stress redistribution within the segmental lining. Therefore several suggestions regarding the design and the numerical discretization have been discussed.

3.2 Shield design

When modifying the segmental lining, it has to be considered that these modifications have to be done for every single element. For a ring with 6 lining segments and an segment width of 2 m, 3000 elements per kilometer have to be modified. Due to that reason a modification on the TBM itself seems reasonable.

When mortar as backfill is applied the backfilling can be realized through the shield tail (see Figure 7) using a two-component system (cement-bentonite suspension with the addition of an accelerator additive) (Thienert 2011). Due to the pumpability of the components a complete backfilled annular gap can be realized at any time. When tunneling in hard rock a backfilling using mortar is not preferable. Hence, using mortar other difficulties occur which are not subject of this research.

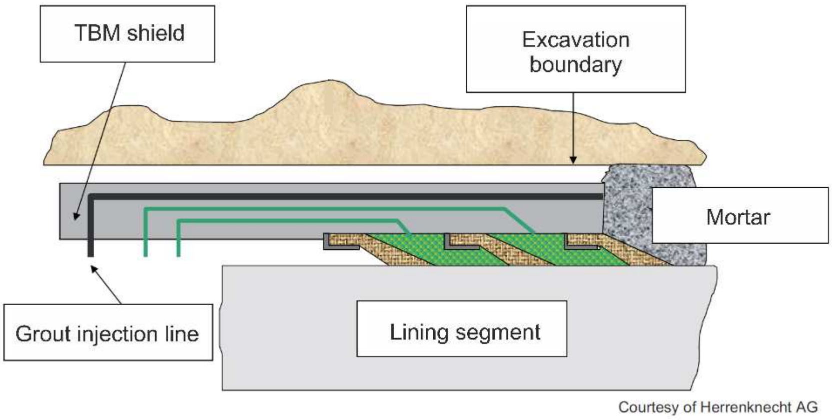

Fig. 7 Mortar injection through the shield tail

Due to the grain size of pea gravel it is pneumatically injected radially through openings in the segments. Therefore, this procedure needs to be performed manually and has to be repeated when the gripper shield advances. When using larger injection pipes through the shield and limiting the upper grain size of pea gravel, this procedure can be applied for pea gravel or a pea gravel and mortar mixture. Therefore, the advantage of pea gravel immediately stabilizing the segments can be realized after every ring closure. This technology is still not proven and the chance of pea gravel clogging the injection lines very high. According to Robbins (2014) the insert opening must have a diameter of at least 70 mm to prevent clogging.
Another approach effects the shape of the shield tail. Allowing the pea gravel to relocate within the annular gap, an angle of repose appears (see Figure 6). An inclined shield tail from bottom to top allows a full contact of the segmental lining with either the backfilling material or the shield at the same time. Hence, the ovalization of the lining segments will be avoided though the deflection forces will cause an increased wear of the tail brushes.

3.1 Lining design

In order to create an immediate contact between the lining and the excavation boundary a novel concept has been developed. Using geotextile tubes placed on the outside of each lining element, the support ring is assembled. The tubes are placed at the end of the segments, so they can be injected using mortar providing a contact with the excavation boundary while the rest of the lining is still protected by the TBM shield. Hence, the geotextile tubes prevent the fully assembled ring of segments to ovalize when leaving the shield tail. The tubes also separate the annular gap into longitudinal sections which prevent the pea gravel from relocating (see Figure 8). Due to the fact, that the invert region is backfilled by a combination of pea gravel and mortar the bottom elements do not need geotextile tubes.
Figure 9 shows the inflation process of the geotextile tubes between two lining segments. The tests have shown good performance. Unfolding of the tubes and establishing full contact along the segment has been accomplished without difficulties.

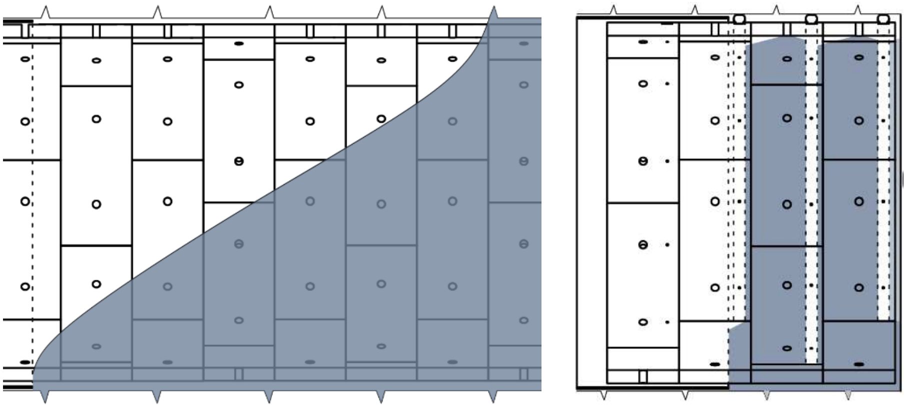

Fig. 8 Relocation of peagravel within the annular gap without (left) and with (right) geotextile tubes placed on the outside of each lining segment

Fig. 9 First operational test of geotextile tubes

3.2 Numerical improvements

To approach this problem we introduced a numerical method that represents the natural behaviour of pea gravel. The Discrete Element Method (DEM) is a CPU-intensive method, which can numerically simulate the natural relocation behaviour.

The Software Abaqus/Explicit implemented the particle method based on „Discrete Element Method“ (Cundall 1971) on their latest update to version 6.13. The main advantage of the Software Abaqus compared to other Discrete Element Method solutions is the possibility of a combination of discrete and finite elements in one model. Using this advantage on that problem, it is possible to model the three dimensional system. Therefore, segments are modelled by using finite elements and the annular gap is modelled by using discrete elements.

As preparation for these calculations, it is necessary to perform validations on laboratory tests. Therefore, some numerical parameter studies on shear and oedometer tests have been made. These numerical tests were validated with real laboratory tests (see Figure 10).

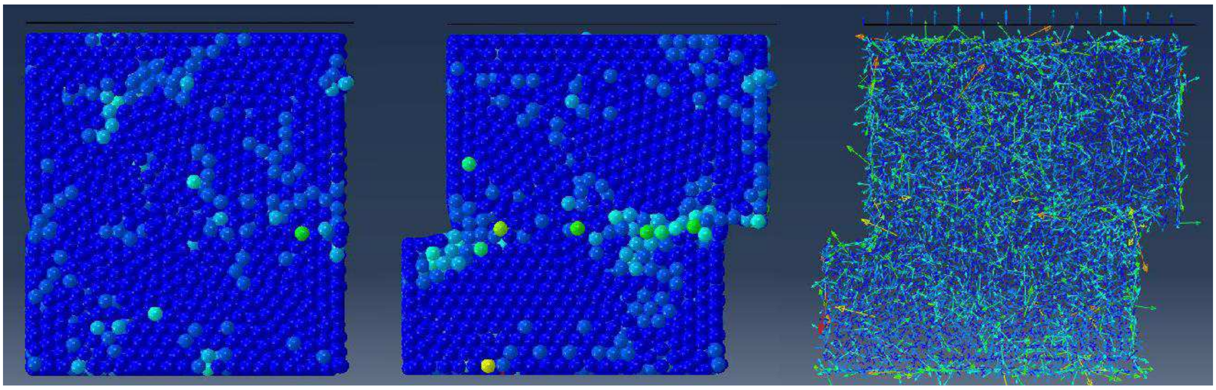

Fig. 10 3D numerical shear test using the software Abaqus – (left) initial state before the hearing process; (middle) velocities of the particles during the shearing process; (right) a contact force vector plot

Due to a bug within the DEM implementation in the Abaqus Code regarding the particle friction, the ground behaviour could not be realistically simulated. Even though Cundall's particle method allows the variation of friction between two particles, the evaluation of the numerical shear tests only resulted in a dilation shown in Figure 11 (Sinkovec 2015).

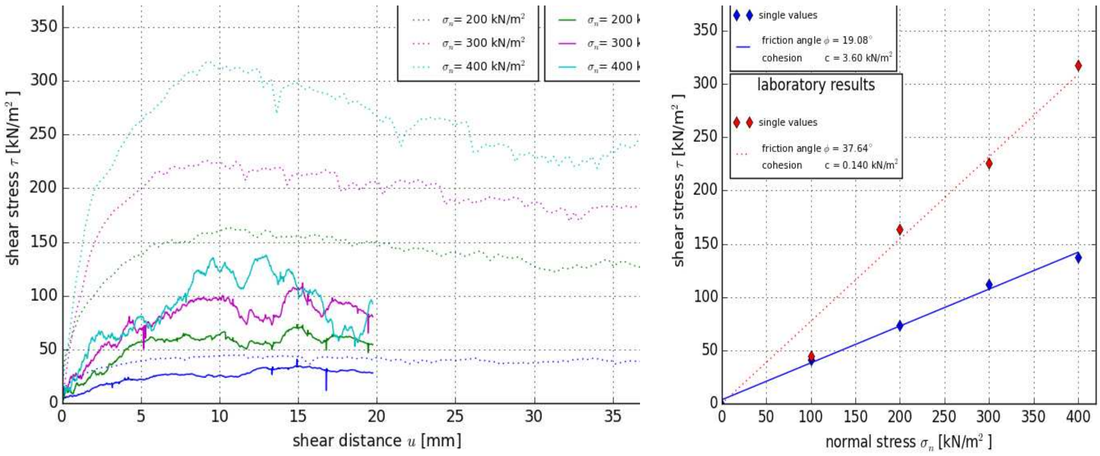

Fig. 11 Validation of shear tests

4 Conclusion

The failure and deformation process of a soil body within the annular gap is a complex process. Numerical state of the art simplifications of the backfilling material regarding the location of pea gravel behind the shield tail are still inaccurate.

1. Numerical simulations indicating stress peaks within the segmental lining are promising. Nevertheless, the deformation process within the annular gap and the subsequent change of bedding behaviour must not be neglected. Therefore, continuum methods are only applicable for this task to a limited extend.
2. If numerical simulations are necessary, the use of discontinuum coupled with continuum methods should be considered.

To avoid damage within the segmental lining improvements regarding the TBM design or the segment design are recommended. Even though alterations of the lining design seem uneconomic they are more easy to implement. Therefore the introduced geotextile tubes seem reliable and promising not only to overcome the ovalization of the segmental lining but also the relocation of pea gravel within the segmental lining.

5 References

AUSTRIAN SOCIETEY FOR CONCRETE- AND CONSTRUCTION TECHNOLOGY, 2011. *Concrete Segmental Lining Systems.* Austrian Societey for Concrete- and Construction Technology.

BEHNEN, G., NEVRLY, T.; FISCHER, O., 2013. *Bettung von Tunnelschalen.* Essen: VGE Verlag. Taschenbuch für den Tunnelbau.

COULOMB, C.A. 1776. Essai sur une application des regles des maximis et minimis a quelques problemes de statique relatifs a l'architecture. In: Memoires de l'Academie Royale pres Divers Savants, 1773(7) pp. 343-382.

CUNDALL, P. A., 1971. A computer model for simulating progressive large scale movements in blocky rock systems. In: Proceedings of the international symposium on rock fracture, Nancy, October 1971. International Society for Rock Mechanics (ISRM), pp 129–136.

KIRSCH, G., 1898. Theorie der Elastizität und die Bedürfnisse der Festigkeitslehre. In: *Zeitschrift des Vereins Deutscher Ingenieure.* **42**(29), pp 797-807.

ÖSTERREICHISCHE GESELLSCHAFT FÜR GEOMECHANIK, 2013. *Richtlinie für die geotechnische Planung von Untertagebauten mit kontinuierlichem Vortrieb*. Österreichische Gesellschaft für Geomechanik.

SINKOVEC, C., 2015: *Investigation of the applicability of Discrete Elements on the backfill of Segments* [Master Thesis]. Graz University of Technology, Graz. Institute for Rock Mechanics and Tunnelling.

THE ROBBINS COMPANY, 2014. *Tunnel Segment Backfilling with Double Shield TBMs* [Powerpoint Presentation]. Solon: The Robbins Company, 2014.

THIELICKE, W., STAMHUIS, E. J. 2014. *PIVlab* [Software]. *Time-Resolved Digital Particle Image Velocimetry Tool for MATLAB.* http://figshare.com/articles/PIVlab_version_1_35/1092508.

THIENERT, C. PULSFORT, M., 2011. Segment design under consideration of the material used to fill the annular gap. In: *Geomechanics and Tunnelling* **4**(6), pp 665–680.