Criterion for Predicting the Risk of a Gripper TBM Jamming

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Jamming or blocking of the cutter head of a tunnel boring machine (TBM) represents a high risk for a tunnel excavation. Extensive investigations have been carried out for tunnel boring machines with shield and double-shield machines and criteria devised for design and dimensioning purposes. These approaches cannot be transposed to tunnelling with a Gripper TBM as the stress deformation behaviour of the rock differs. This article examines three-dimensional numerical parameter studies for analysing the stress deformation behaviour of the rock for excavations using a Gripper TBM and diagrams subsequently derived from them for estimating the risk of a Gripper TBM jamming.

Tunnelling • Excavation • TBM • Gripper • Risk • Modelling

1 Introduction

Large, protracted deformations of the excavated cavity are formed when tunnelling in squeezing rock. As a result, tunnel boring machines (TBMs) can jam or their cutter heads can block. A well-known example in this case is the drive involving a Gripper TBM when building the Gotthard Base Tunnel in Switzerland [1 to 4]. Further examples of TBMs jamming can be found in [5 to 7]. One possibility of preventing a TBM jamming is to execute an overbreak by means of the disc cutters fixed to the cutter head.

In the past, the selected size of the overbreak was established by reference values from accomplished projects. Extensive investigations were undertaken for tunnel boring machines with shield (TBM-S) and double shield machines (DSM) and criteria for design and dimensioning purposes developed [8 to 17]. These criteria or approaches cannot simply be applied for excavating with a Gripper TBM. In comparison with driving with a TBM-S or a DSM, in the case of which the cavity is supported directly by installing the segmental lining, the rock in the case of a Gripper TBM drive is first scheduled to be secured in the Gripper TBM's back-up area by means of a shotcrete support. This area was established at a gap of 46.5 m from the face for the drives for the Gotthard Base Tunnel for example [4]. When the rock has to be supported unexpectedly, anchors, shotcrete and support arches for example can be installed directly behind the cutter head in the case of drives involving a Gripper TBM in unstable rock. However, this leads to a clear reduction of the rate of advance thus exerting an influence on a Gripper TBM's economy. This signifies that in the case of a scheduled drive with a Gripper TBM a relatively large or long area of excavated cavity exists in the rock, which is not supported by a lining and in which the rock can deform without being hampered. In this way, the stress deformation behaviour of the rock in the case of an excavation with a Gripper TBM deviates most pronouncedly from the stress deformation behaviour of the rock in the case of a drive with a TBM-S or DSM [19].

In order to be in a position to analyse the stress deformation behaviour of the rock during a drive with a simple pretensioned Gripper TBM, a three-dimensional numerical calculation model was developed [19, 20]. Parameter studies were undertaken using this calculation model, in the case of which the physical parameters and the overburden height of the rock were varied. Diagrams were developed from the results of the parameter studies, by means of which the displacements occurring during a Gripper TBM drive are estimated and the risk of a Gripper TBM jamming can be predicted.

2 Three-dimensional numerical Calculation Model

The three-dimensional numerical model that was developed represents the complete construction cycle of an excavation using a simple pretensioned Gripper TBM. Fig. 1 shows the numerical calculation model with the individually modelled areas. The geometrical dimensions, the material characteristic values and the construction cycle correspond with those during a Gripper TBM excavation in individual sections of the Gotthard Base Tunnel [19, 20]. The model dimensions are shown in Fig. 2. A tunnel diameter of d = 9.5 m was assumed. On the basis of prior investigations and recommendations by the working group 1.6 "Numerics in Geotechnics" of the DGGT [29], a distance of 77 m, in other words eight times the diameter 8d, from the lateral model edge and a gap of 48 m, in other words five times the diameter 5d from the lower model edge were applied. The total length of the calculation model amounts to 230 m. The excavated section shown in the calculation model was set at 190 m.

Homogeneous rock behaviour was assumed for the depicted ground. For this purpose the physical characteristics of the ground were simulated by a linear-elastic ideal plastic constitutive equation with the flow criterion according to Mohr-Coulomb and non-associated

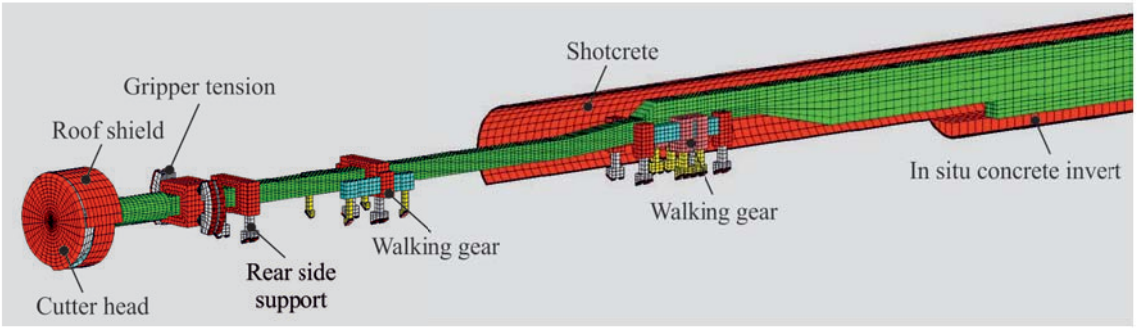


Fig. 1: Numerical calculation model for the Gripper TBM
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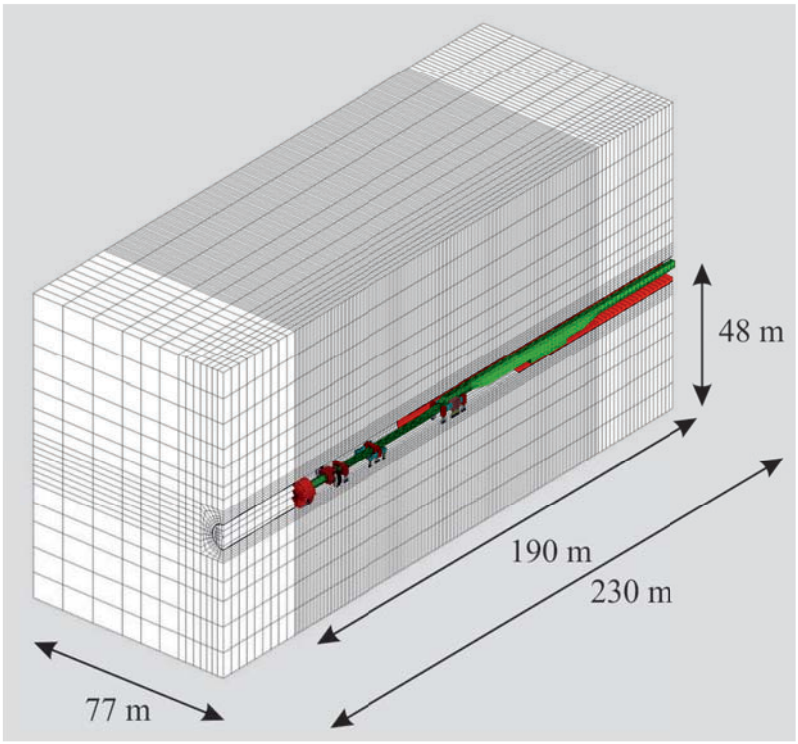
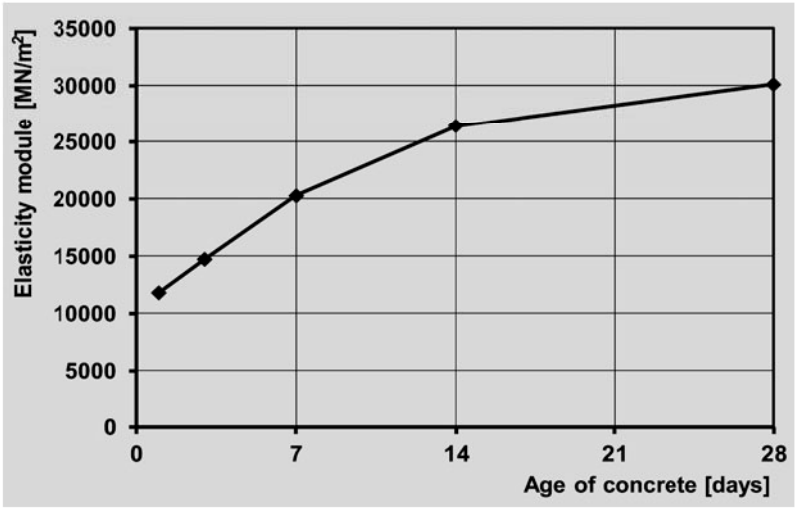


Fig. 2: Three-dimensional numerical model for Gripper TBM with presentation of the simulated ground

Fig. 3: Time-related development of the elasticity module for a C20/25 concrete



flow rules. The steel structural parts of the Gripper TBM were depicted by a linear-elastic material behaviour as well as equivalent stiffnesses and equivalent weights applied in parts. The in situ concrete invert and the shotcrete for the necessary temporary support were also described by a linear-elastic material behaviour. In this connection, the elasticity module for the in situ concrete invert and the shotcrete were adjusted in keeping with construction progress for a predetermined rate of advance of 13 m/day in order to simulate the time-related setting of the concrete [18, 19]. The compressive strength was correspondingly converted in the elasticity module (Fig. 3) according to [22]. The shotcrete shell and the in situ concrete invert were taken into consideration with a Poisson ratio of $\mu = 0.2$ and a specific weight of $\gamma = 24$ kN/m³.

The individual driving phases such as the individual strokes, the implementation of the grippers and the relocating of the advancing gear are simulated in the spatial calculations. These calculations were undertaken in the form of a step-by-step analysis for the results which are presented here.

3 Parameter Studies

Extensive sensitivity studies were carried out using the previously described numerical model so that the theoretical stress deformation behaviour of the rock in the case of a mechanised tunnel drive with a Gripper TBM could be examined. Taking the isotropic material properties of the rock into consideration the rock characteristic values and the overburden height h were varied in the sensitivity studies. Table 1 shows the individual parameters with the varied ranges. It should be observed that the lower parameters for the elasticity module of the rock E_{rock} and the cohesion of the rock c_{rock} represent borderline cases.

4 Calculation Results

The vertical displacements in the roof were defined as decisive for contemplating the displacements in the excavated cross-section as they exceeded the calculated values of the displacements in the wall and the invert. Fig. 4 shows the vertical displacements in the roof visualised for different sets of parameters. Towards this end the vertical displacements are shown depending on the

Table 1: Range of applied rock parameters with isotropic characteristics and overburden height

Parameter	Unit	Range
Specific weight γ_{rock}	[kN/m³]	26
Elasticity module E_{rock}	[MN/m²]	500 to 5,000
Poisson ratio μ_{rock}	[-]	0.2
Angle of friction φ_{rock}	[°]	25 to 40
Cohesion c_{rock}	[MN/m²]	0.1 to 2.0
Overburden height h_o	[m]	100 to 800

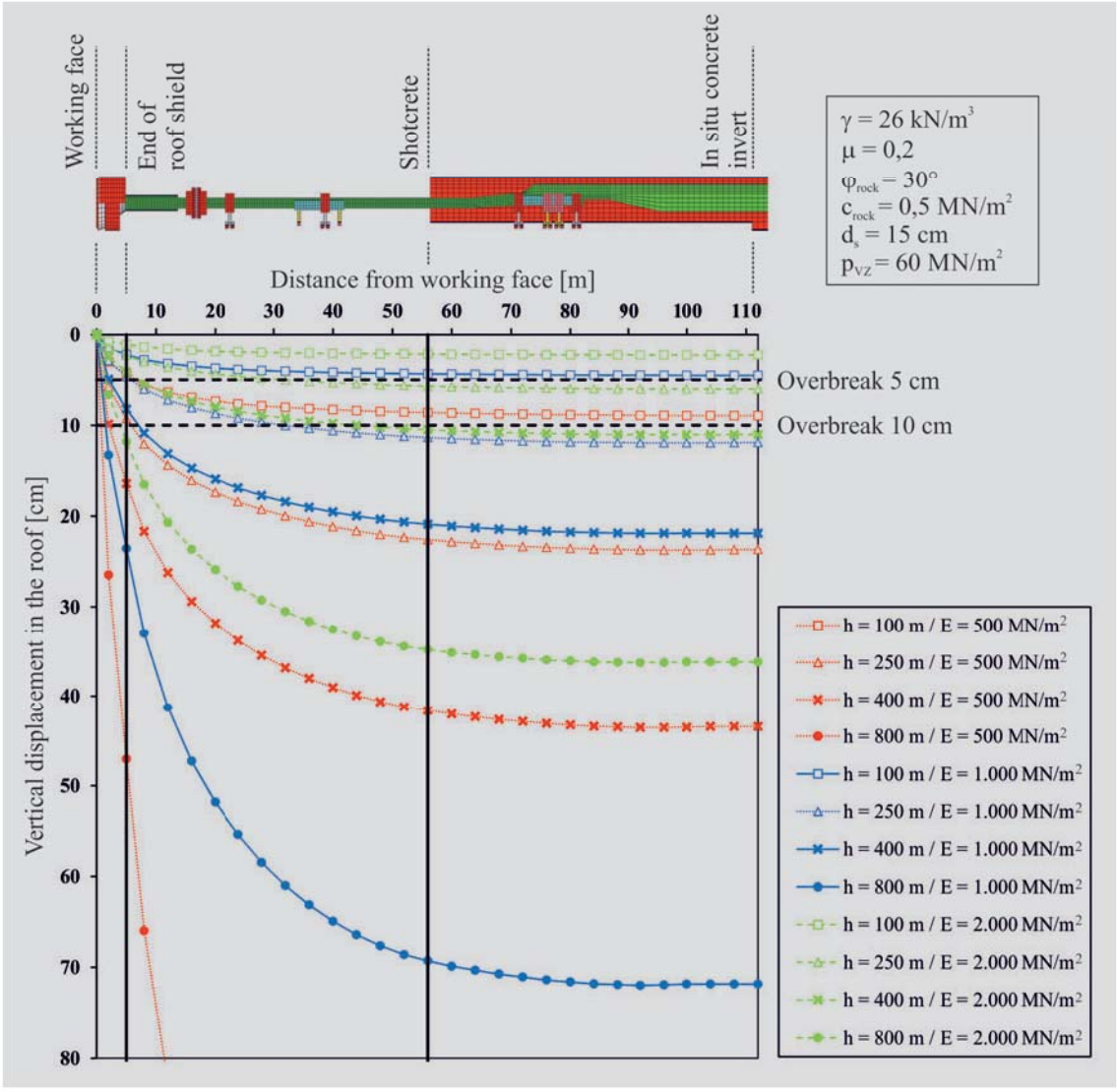
distance to the face. The individual curves form the varied overburden heights h and the different elasticity moduli of the rock E. As the overburden height h increases and the elasticity module of the rock E decreases, the vertical displacements in the roof become greater as expected. The largest part of the vertical displacements in the roof ceases when the temporary shotcrete support is installed as the excavated area is secured once the temporary shotcrete support has been placed.

Two particular areas are decisive for a Gripper TBM jamming when driving with a Gripper TBM. First of all, there is the risk that the cutter head can block owing to major displacements; secondly the displacements in the unsupported area are so large that the back-up section can no longer be advanced.

In the proximity of the roof shield, roof displacements occur in the calculations for a "soft" rock as well given a shallow overburden height of 100 m in the case of the contemplated shear strengths of the rock, which are non-critical for the excavation and do not lead to the cutter head jamming. On the other hand, the risk of the cutter head jamming grows very quickly overproportionally given greater overburdens (Fig. 4).

A large proportion of the displacements occur in the area between the cutter head and the area where the temporary shotcrete support is installed. This factor can influence the back-up system being advanced. Roof

Fig. 4: Vertical displacements in the roof dependent on the distance to the face in the longitudinal direction of the tunnel for different overburden heights h and E-moduli E of the rock

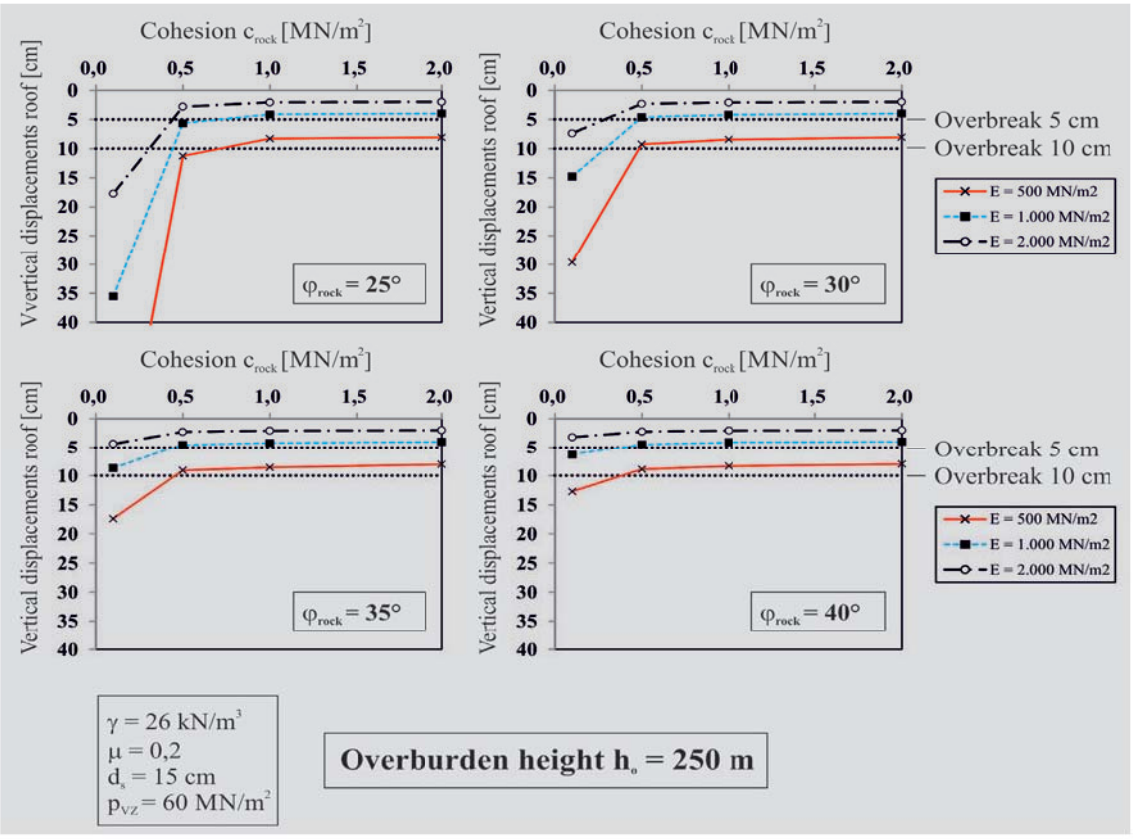


displacements occur here as in the case of the area of the cutter head for a "soft" rock given a shallow overburden height of 100 m in the case of the contemplated shear strengths of the rock, which are considered non-critical for the excavation. Here too, displacements are to be observed in the excavated area given greater overburdens, which must be assessed as critical for advancing the back-up system (Fig. 4).

In the presented results, on the one hand, the very great influences exerted by the overburden height h and the elasticity module of the rock E are evident, and on the other, the determining displacements occur in the area from the face to the one in which the temporary shotcrete support is installed. Once the temporary shotcrete support has been installed, the increase of the vertical displacements in the roof is only relatively slight. This can of course, be attributed to the fact that the rock is secured by the temporary shotcrete support thus hampering further displacements.

Fig. 5 serves to compare and analyse the influence of shear strengths and the elasticity module at the cutter head based on the results of the parameter studies. In this case, the overburden height is taken to be h_0 = 250 m. The elasticity module and the shear strengths of the rock were varied. The cohesion of the rock c_{rock} is presented as it increases from left to right on the abscissa axis and the vertical displacements in the roof shown on the increase from top to bottom on the ordinate axis. The individual diagrams in each case represent the different variations of the rock's angle of friction ϕ_{rock} and the three curves form the different elasticity moduli of the rock E. When considering the influence of cohesion on the vertical displacements it is obvious that as the cohesion increases the vertical displacements greatly decrease. If the rock possesses low cohesion, which attains a state of failure more rapidly, the plastic deformations are correspondingly large. As the cohesion grows the overall vertical displacements depend almost solely on the elastic properties of the rock so that the shear strengths exert merely a slight effect on the size of the displacements. The vertical displacements are still relatively large within the range of the extreme values of cohesion c_{rock} from 0.1 to 0.5 MN/m² as the shear strengths are slight and the rock, as previously described, attains a state of failure more rapidly. However, the vertical displacements in the case of cohesion greater than or equalling 0.5 MN/m² are relatively slight and decrease only moderately given increasing cohesion. The analyses relating to shear strengths also indicate that the angle of friction also exerts an influence on the amount of vertical displacement. However, this influence is less than the influence of cohesion. The influence of the angle of friction becomes negligibly small as from a cohesion greater than or equalling 0.5 MN/m² and the plastic deformations become negligibly small on account of the angle of friction. As the cohesion in the 0.1 to 0.5 MN/m² range relates to an extreme value and the values do not characterise stable

Fig. 5: Vertical displacements in the roof in the cutter head area at the end of the roof shield depending on the cohesion of the rock for overburden and different angles of friction φ and E-moduli E



rock or stable solid rock, it can be said that generally speaking, the vertical displacements owing to the plastic deformations of the rock are if anything dependent on cohesion with the angle of friction only possessing a less significant influence. Furthermore, it can be discerned that the deformation proportions from the elasticity module (elastic proportion) are considerably larger compared with the deformation proportions from the shear strengths (plastic proportion). It can be concluded after consideration of the case c_{rock} greater than or equalling 0.5 MN/m² that the influence on the vertical displacements largely depends on the elasticity module. In this case, the rock does not attain the state of failure or only to a small extent owing to the high shear strengths so that the vertical displacements of the rock largely result from the influence of the elasticity module. Accordingly it is shown by this comparison that by increasing the elasticity module the vertical displacements decrease drastically. This behaviour is also to be observed given low shear strength. As a result, the elasticity module in contrast to the shear strengths exerts a greater influence on each type of variation. The previously cited conclusions applying to the cutter head area can also be ascertained in the back-up area without temporary shotcrete support.

Fig. 6 shows exemplarily the vertical displacements in the roof in the cutter head area depending on the overburden height and the elasticity module of the rock for a 30° angle of friction and 0.5 MN/m² cohesion. The overburden height h_o increasing from left to right is presented on the abscissa axis and the vertical displacement of the roof on the increase from top to bottom shown on the ordinate axis. The curves form the different elasticity moduli of the rock.

When considering the influence of the overburden height on the vertical displacements it must be observed that the vertical displacements increase in accordance with the overburden height. It can be discerned most clearly from Fig. 6 that the vertical displacements in the roof grow overproportionally in keeping with the overburden height. The influence of the overburden height on the size of the vertical displacements is evident in spite of the growing elasticity module of the rock and can thus not be neglected. The previously cited conclusions relating to the cutter head area are also evident here in the back-up area without temporary shotcrete support.

5 Dimensioning Diagrams

The sensitivity studies that were undertaken indicate that the parameters overburden height, elasticity module of the rock as well as cohesion of the rock exercise decisive influence on the vertical displacements in the roof in the cutter head area and in the back-up area without temporary shotcrete support. The parameter angle of friction of the rock also exerts an influence on the vertical displacements in the roof. However, here the influence is not so strongly in evidence as in the case of the previously cited parameters. On the basis of the results of the parameter studies diagrams were developed by means of which it is possible to estimate the displacements, which occur when tunnelling with a Gripper TBM so that a prediction can be provided with regard to the risk of jamming when using a Gripper TBM for instance in the scope of a feasibility study.

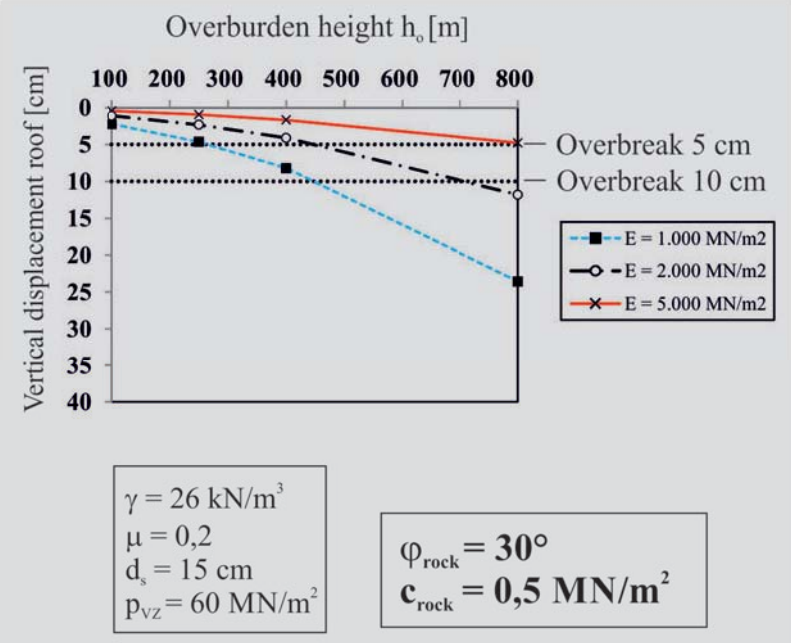


Fig. 6: Vertical displacements in the roof in the cutter head area at the end of the roof shield depending on the overburden height of the rock for different E-moduli E

The diagrams are in this case produced for the two decisive areas for three rock elasticity module alternatives. Section 5.1 shows the diagrams for the cutter head area. The cutter head area is in this case defined as the end of the roof shield according to Fig. 4. The diagrams for the back-up area are presented in Section 5.2. In this case the back-up area in keeping with Fig. 4 is defined as the point in the back-up section, where the temporary shotcrete support begins.

5.1 Cutter Head Area of the Gripper TBM at the End of the Roof Shield

Figs. 7 to 9 display the vertical displacements, which in accordance with Fig. 4 occur in the roof in the cutter head area at the end of the roof shield, increasing from top to bottom depending on the cohesion of the rock increasing from left to right. Fig. 7 shows the vertical displacements for an E-module of the rock of 500 MN/m², Fig. 8 for an E-module of 1,000 and Fig. 9 of 2,000 MN/m². Each image contains four diagrams for four different angles of friction. The four curves of the individual diagrams depict various overburden heights.

5.2 Back-Up Area of the Gripper TBM

Maximum displacements in the roof placed at the point, where the temporary shotcrete support begins, are depicted in Figs. 10 to 12 for the back-up area, in similar fashion to Figs. 7 to 9 explained in Section 5.1.

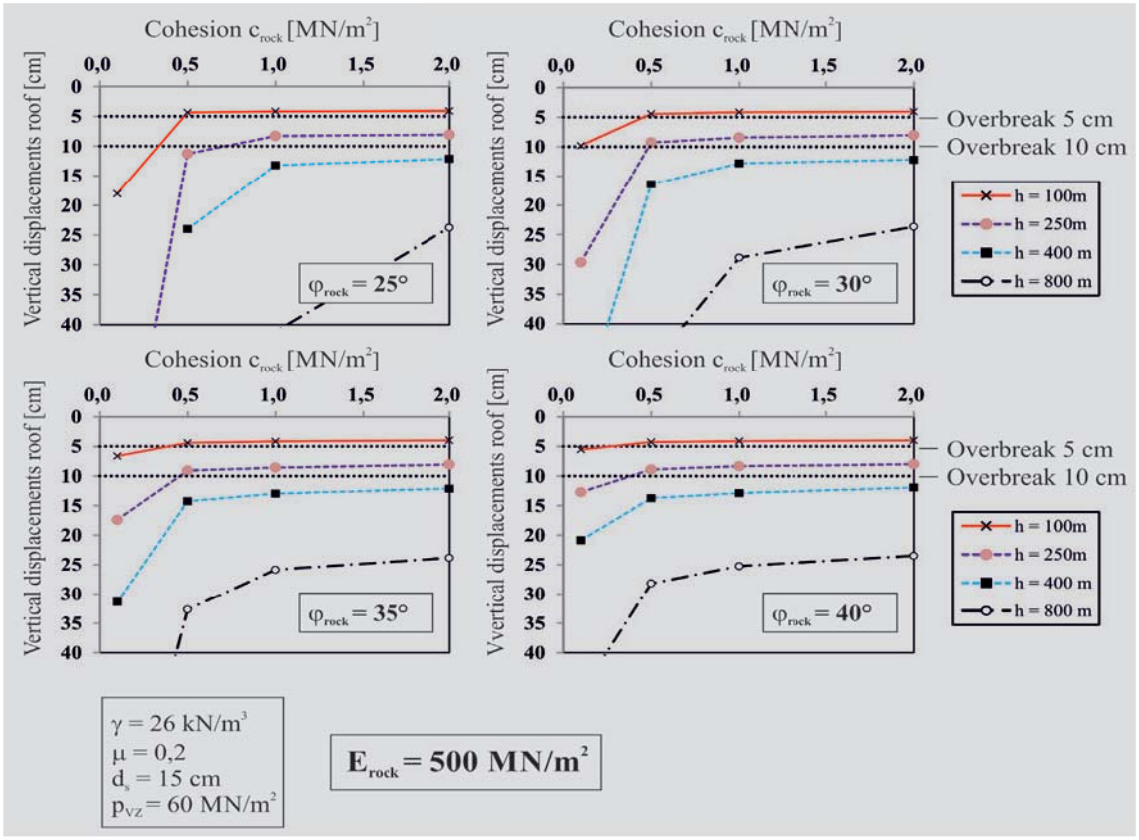
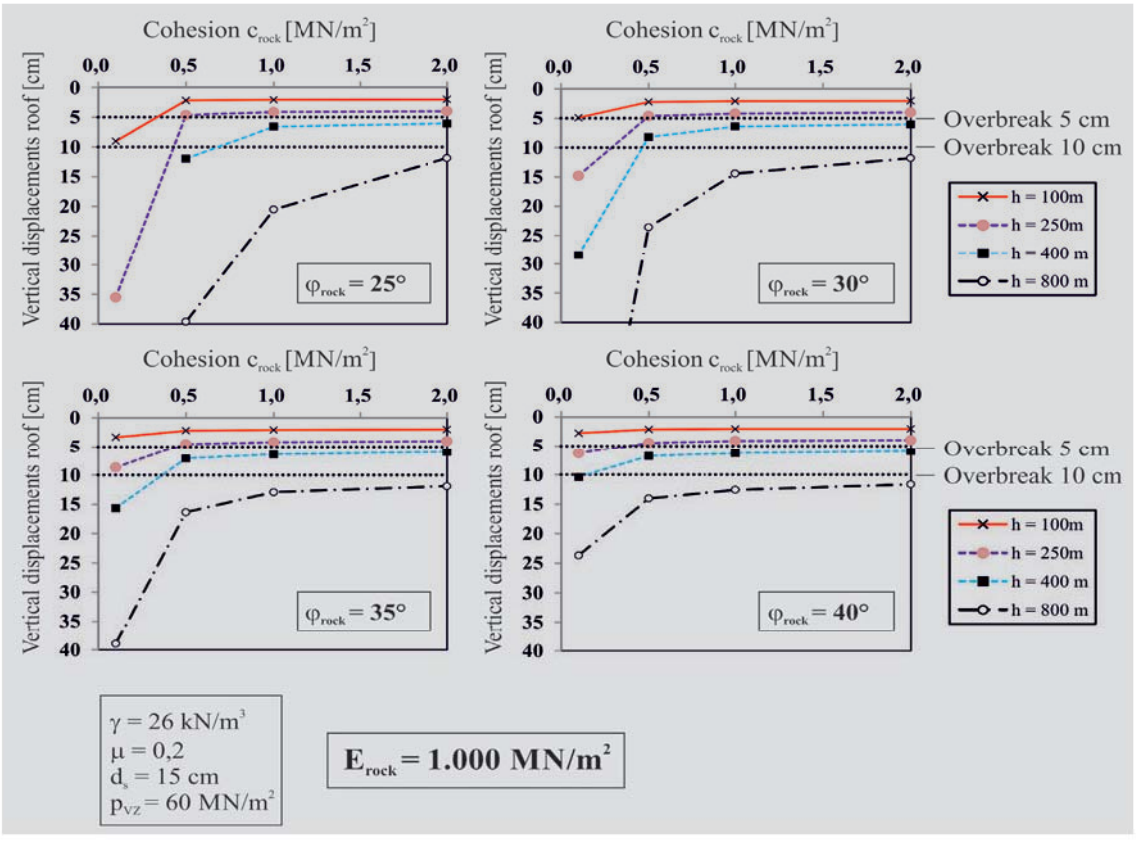


Fig. 7: Vertical displacements in the rock in the cutter head area depending on the cohesion of the rock for E-module E of 500 MN/m² and various angles of friction φ and overburden heights h

Fig. 8: Vertical displacements in the roof in the cutter head area depending on the cohesion of the rock for E-module E of 1,000 MN/m² and various angles of friction φ and overburden heights h



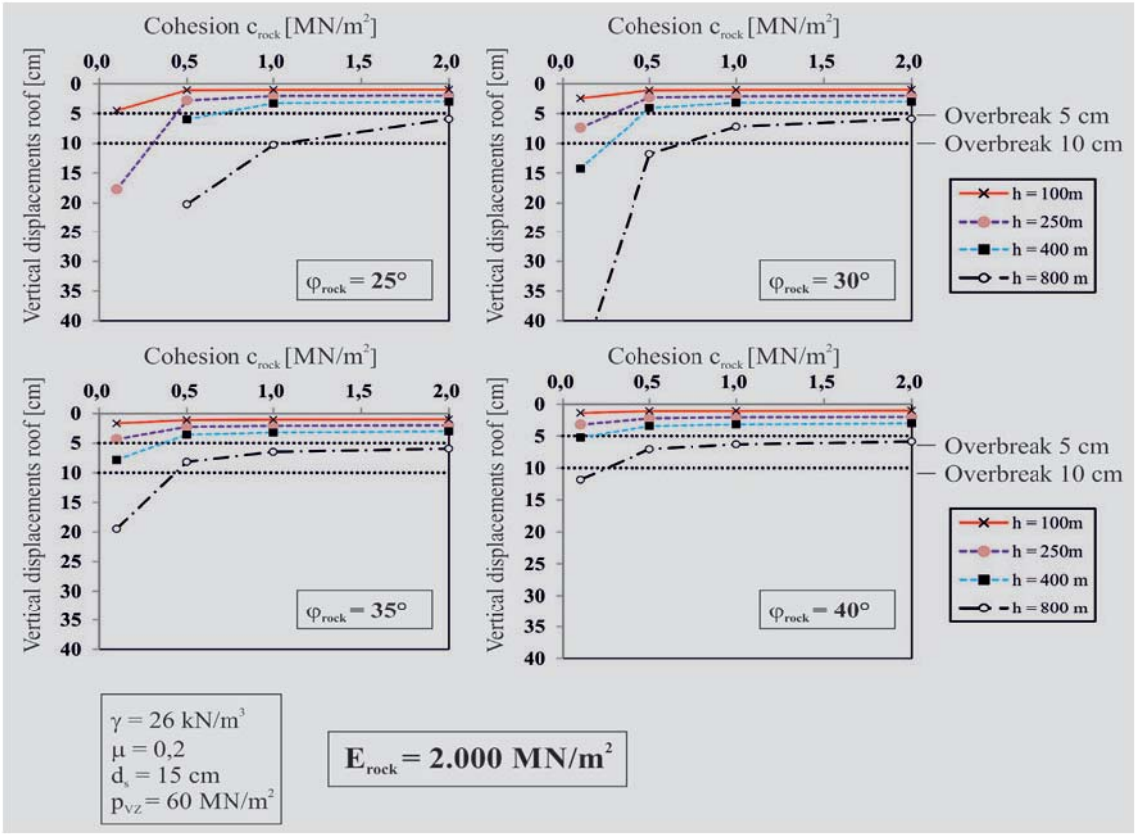


Fig. 9: Vertical displacements in the roof in the cutter head area depending on the cohesion of the rock for E-module E of 2,000 MN/m² and various angles of friction φ and overburden heights h

6 Conclusion and Outlook

Jamming or blocking of the cutter head represents a high risk for the excavation when tunnelling with a TBM. The criteria and approaches developed for designing and dimensioning drives using a tunnel boring machine with shield and for double shield machines cannot be transposed for tunnelling with a Gripper TBM. As a result, in order to be able to analyse the rock's stress deformation behaviour during a drive with a simple pretensioned Gripper TBM, three-dimensional numerical parameter studies were carried out. The physical parameters of the simulated rock and the overburden height were varied in these studies.

The results indicate that the overburden height, the elasticity module as well as the cohesion of the rock exert a decisive influence on the vertical displacement in the roof. This is, in turn, decisive for predicting the risk of a Gripper TBM jamming in the proximity of the cutter head and the back-up area.

Diagrams were developed from the results of the parameter studies, which facilitate the displacements while tunnelling with a Gripper TBM to be estimated and in turn, a forecast of the risk of a Gripper TBM jamming, for example, in the form of a feasibility study.

The results relate to idealistic models and calculation assumptions. Measurement technical verification is still lacking owing to the fact that the measurement data from projects are still incomplete. The influence of separation planes on the stress deformation behaviour of the rock while driving with a Gripper TBM has still to be analysed in further parameter studies through applying appropriate physical laws in the numerical calculation model.

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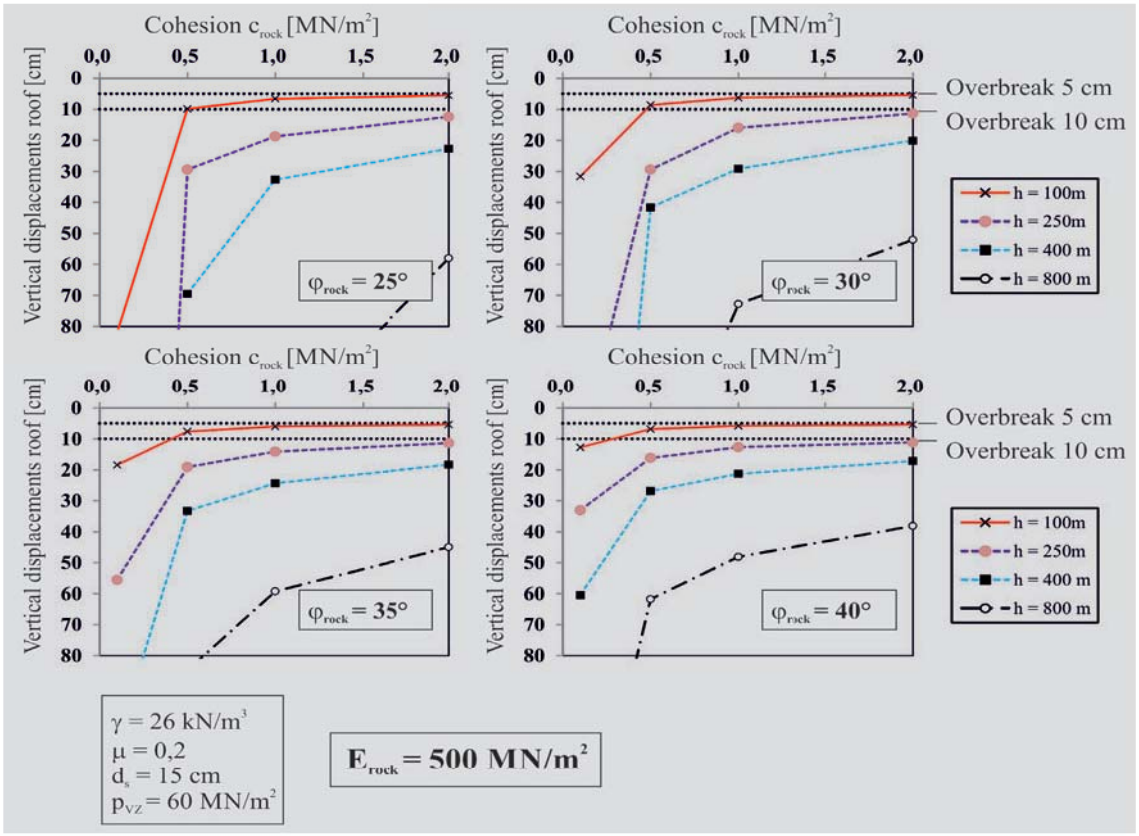
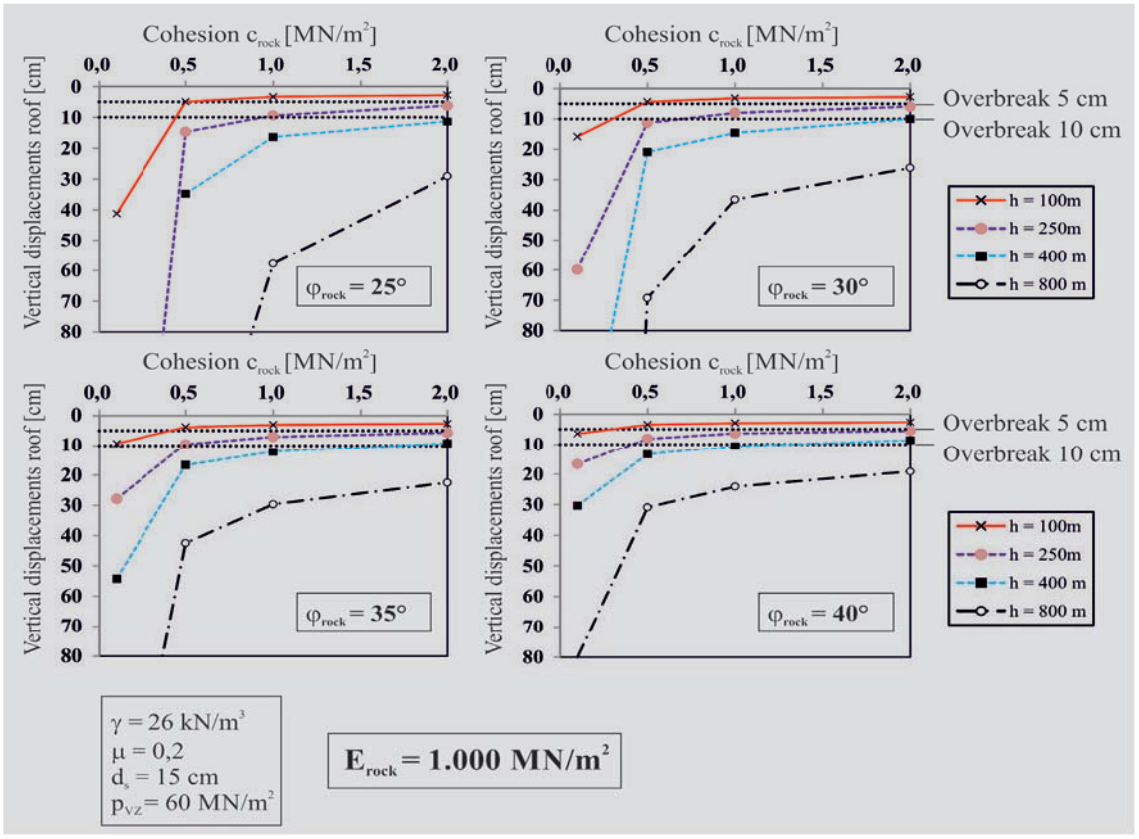


Fig. 10: Vertical displacements in the roof in the back-up area depending on the cohesion of the rock for E-module E of 500 MN/m² and various angles of friction φ and overburden heights h

Fig. 11: Vertical displacements in the roof in the back-up area depending on the cohesion of the rock for E-module E of 1,000 MN/m² and various angles of friction φ and overburden heights h



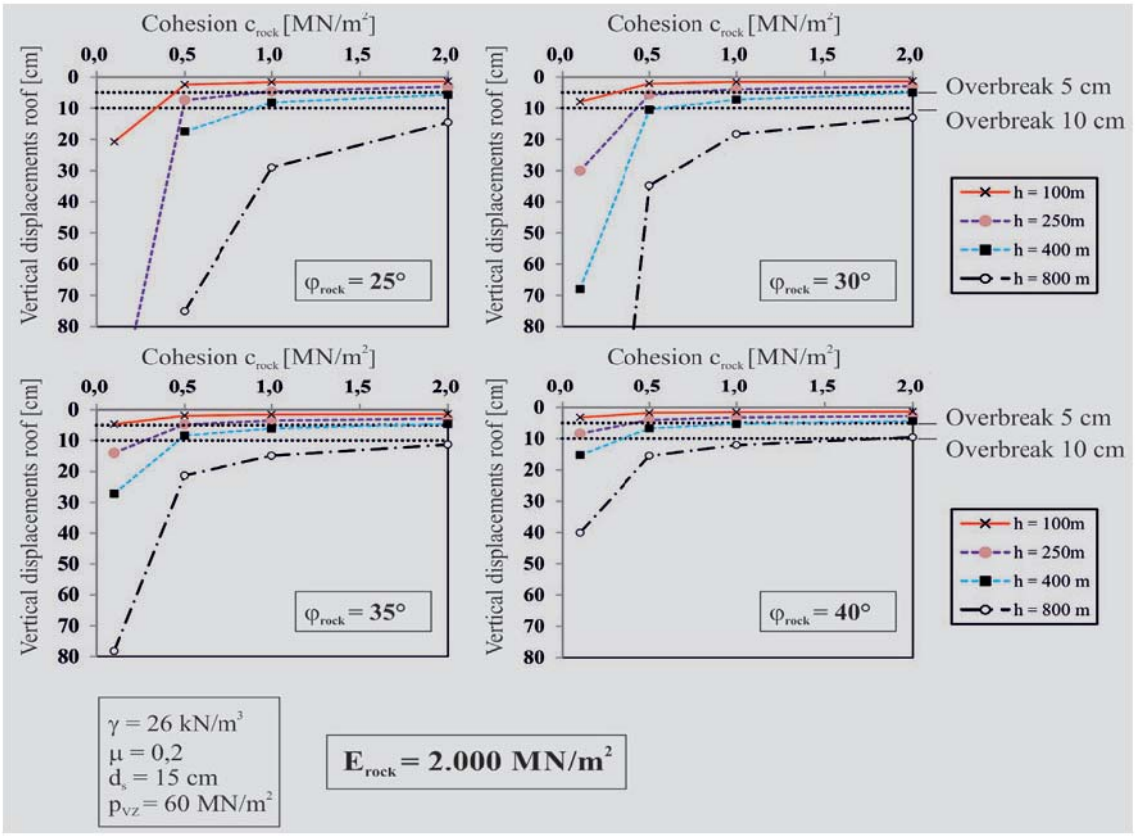


Fig. 12: Vertical displacements in the roof in the back-up area depending on the cohesion of the rock for E-module E of 2,000 MN/m² and various angles of friction φ and overburden heights h

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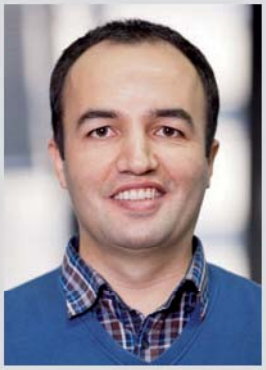
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