



Berg Huettenmaenn Monatsh (2023) Vol. 168 (12): 586–595
<https://doi.org/10.1007/s00501-023-01413-9>
 © The Author(s) 2023

BHM Berg- und
Hüttenmännische
Monatshefte

Expanding the Scene of Tunnel Behaviour Through the DEM Model: a Case Study from ZaB-Zentrum Am Berg

Khomchan Promneewat¹, Cheowchan Leelasukseree², Marlene Villeneuve³, and Robert Galler³

¹NATM Engineering program, Institute of Rock Mechanics and Tunnelling, Graz University of Technology, Graz, Austria

²Department of Mining and Petroleum Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai, Thailand

³Subsurface Engineering, Montanuniversität Leoben, Leoben, Austria

Received October 29, 2023; accepted November 6, 2023; published online December 9, 2023

Abstract: The displacement of a tunnel plays a crucial role in conventional tunneling methods, serving as a key parameter for support requirement. Therefore, analyzing tunnel displacement is important for ensuring safety and optimizing costs by determining the appropriate level of tunnel support and installation time. Numerical analysis methods are commonly employed for assessing tunnel displacement, and two widely recognized approaches used worldwide are the continuum and discontinuum methods. While previous studies have highlighted differences in the analysis results obtained from these two methods, the magnitude of such disparities has not been extensively explored. Hence, the objective of this study is to quantify the extent of variation between the two methods through various scenarios, encompassing unsupported and supported excavated ground. Specifically, the focus is on tunnel displacement and the tensile force generated on axial tunnel supports, such as rock bolts. To facilitate this investigation, three tunnel sections from the Zentrum am Berg, tunnel research centre located in Austria, are utilized. The results show that discontinuum models exhibit higher displacements and higher tensile loads on axial support than continuum numerical models of the same tunnel geometry and equivalent rock masses. We show that discontinuum models can also capture asymmetric behaviour, and thus should be preferentially used in fractured rock masses where displacement of rock blocks dominate the rock mass behaviour.

Keywords: Numerical analysis, Discrete Element Method, Finite Element Method, Tunnel behaviour, Zentrum am Berg

Die Erweiterung der Szene des Tunnelverhalten durch das DEM-Modell: Eine Fallstudie aus dem ZaB-Zentrum am Berg

Zusammenfassung: Die Verschiebung eines Tunnels spielt bei konventionellen Tunnelbauverfahren eine entscheidende Rolle und dient als Schlüsselparаметer für den Ausbaubedarf. Daher ist die Analyse der Tunnelverschiebung wichtig, um die Sicherheit zu gewährleisten und die Kosten zu optimieren, indem das angemessene Niveau der Tunnelunterstützung und die Installationszeit bestimmt werden. Numerische Analysemethoden werden üblicherweise zur Bewertung von Tunnelverschiebungen eingesetzt, und zwei weltweit anerkannte Ansätze sind die Kontinuums- und die Diskontinuumsmethode. Frühere Studien haben zwar die Unterschiede zwischen den Analyseergebnissen dieser beiden Methoden aufgezeigt, das Ausmaß dieser Unterschiede wurde jedoch noch nicht eingehend untersucht. Ziel dieser Studie ist es daher, das Ausmaß der Unterschiede zwischen den beiden Methoden anhand verschiedener Szenarien zu quantifizieren, die sowohl ungestützten als auch gestützten Aushub umfassen. Das Hauptaugenmerk liegt dabei auf der Tunnelverschiebung und der Zugkraft, die auf axiale Tunnelausbauten, wie z. B. Felsbolzen, wirkt. Für diese Untersuchung werden drei Tunnelabschnitte aus dem Zentrum am Berg, einem Tunnelforschungszentrum in Österreich, herangezogen. Die Ergebnisse zeigen, dass Diskontinuumsmodelle höhere Verschiebungen und höhere Zugbelastungen auf axialen Stützen aufweisen als numerische Kontinuumsmodelle der gleichen Tunnelgeometrie und äquivalenter Gebirgsmassen. Wir zeigen, dass Diskontinuumsmodelle auch asymmetrisches Verhalten erfassen können und daher bevorzugt in zerklüfteten Gesteinsmassen

M. Villeneuve (✉)
Subsurface Engineering,
Montanuniversität Leoben,
Franz-Josef Straße 18,
8700 Leoben, Austria
marlene.villeneuve@unileoben.ac.at

eingesetzt werden sollten, bei denen die Verschiebung von Gesteinsblöcken das Verhalten der Gesteinsmasse dominiert. ur.

Schlüsselwörter: Numerische Analyse, Diskrete Elemente Methode, Finite Elemente Methode, Tunnelverhalten, Zentrum am Berg

1. Motivation

In tunnel design, there are instances where an analytical design method, such as the convergence-confinement method [1], is insufficient to obtain a reliable design. This is due to the numerous rock mass and support parameters that need to be considered and the heterogeneity, variability, and uncertainty associated with geological materials. To address this, numerical analysis is used to evaluate tunnel stress, displacement, and stability of excavations. Two commonly used numerical analysis approaches for this are continuum and discontinuum. These methods employ different underlying principles to represent rock masses. With a continuum approach, the jointed rock mass is modelled as an equivalent continuous medium, whereas with a discontinuum approach, discontinuities are explicitly modelled. Normally a continuum method is only appropriate if the rock mass is sufficiently jointed as to behave as an equivalent isotropic continuum [2]. Where the rock blocks are on the scale of the excavation, a continuum approach is no longer appropriate and a discontinuum is necessary. Figure 1 illustrates a contrasting result obtained

from these two methods for tunnel design in a jointed rock mass, where the discontinuum model illustrates the development of a non-continuous stress distribution in the system compared to the continuum model, as well as discontinuous deformation of the excavation. This highlights the need to account for localized behaviour in such a fractured rock mass via a discontinuum approach.

Given the discrepancies between the results obtained from continuum and discontinuum models, this research aims to explore and quantify the disparity between these two approaches, focusing on displacement and loading on the axial support. This study serves as an example of the selection process for appropriate numerical modelling tools in underground construction.

2. Numerical Analysis Approach

2.1 Continuum: Finite Element Method

In this approach, the object is partitioned into smaller units, referred to as elements (Fig. 2b). Each element is bounded by nodes at the corners (Fig. 2c). The nodes from adjacent elements overlap each other thereby creating a mesh. The elements and nodes exhibit specific values representing the analyzed quantity, like force (node; eg. F_1 and F_2 in Fig. 2b), displacement (node), stress (element), or strain (element). To determine the unknown values within each element and for each node during the computation, different solving techniques are used. In the finite element method (FEM), the element and node values are represented by

Fig. 1: The stress distribution comparison presented in Barton [3], between continuum (a) and discontinuum (b)

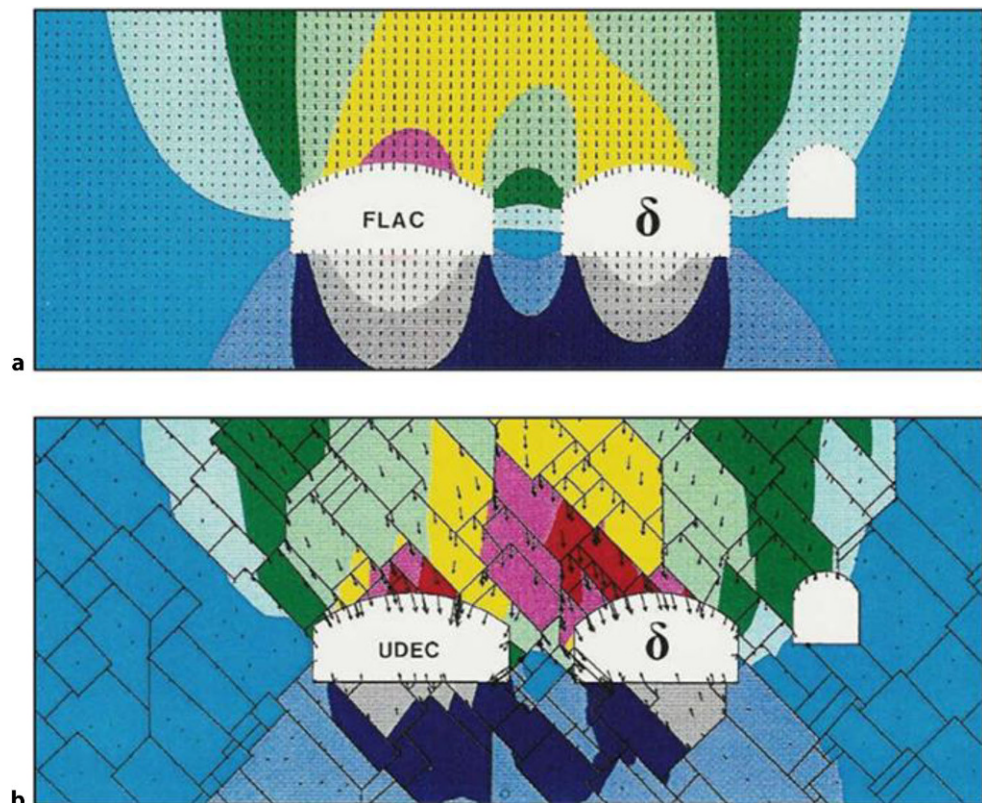
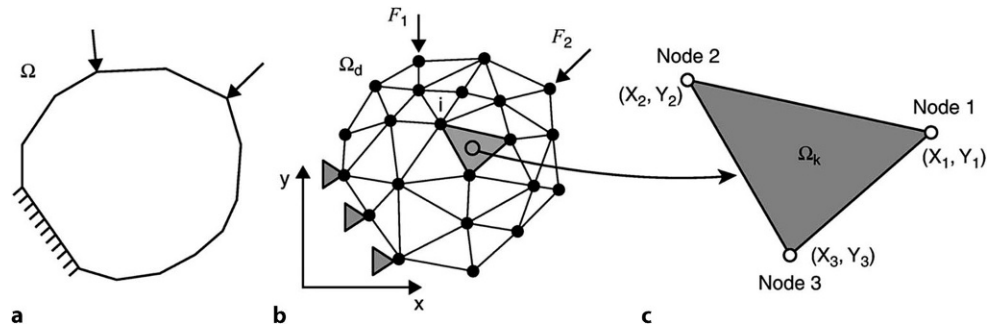


Fig. 2: Graphic representation of the discretization of an object (a) into a connected mesh (b) consisting of nodes and elements (c) [4]



polynomial functions, which are placed in a matrix. All equations are solved concurrently over a series of iterations.

2.2 Discontinuum: Discrete Element Method

This method involves breaking the material into individual discrete elements that interact with each other through contact forces, allowing for the modelling of complex mechanical behaviour. The Hertz theory, first proposed by Hertz [5], serves as the contact mechanic principle to determine the interaction between the elements. By tracking the contact force history and the motion of each element in the model (Fig. 3), a holistic simulation of the system can be generated.

3. Study Area

This study consisted of a modeling analysis of tunnel sections within the Zentrum am Berg (ZaB). ZaB is a research facility focused on underground construction, situated in the Erzberg mine, in Eisenerz, Austria [7]. ZaB layout is represented in Fig. 4. The Zentrum am Berg exhibits a geology primarily characterized by the prevalence of five distinct rock units. These include ankerite/siderite, carbonate rock, Blasseneck porphyry, phyllite/Eisenerz strata, and loamy ground. The area is within the Nordic Nappe, a geological unit situated in the Greywacke zone of northern Styria, Austria [8].

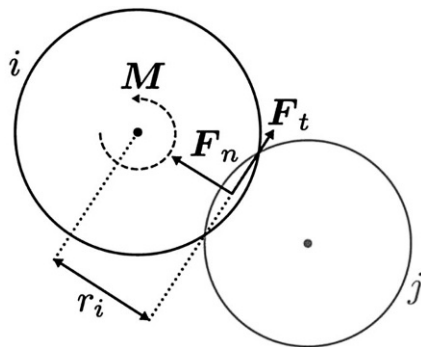


Fig. 3: Depiction of a contact force (divided into normal (F_n) and tangential (F_t) components) and the resulting motion experienced by the particle using the discrete element method [6]

4. Methods and Materials

4.1 Sections

A total of three tunnel sections were selected, comprising two sections from the railway tunnel and one section from

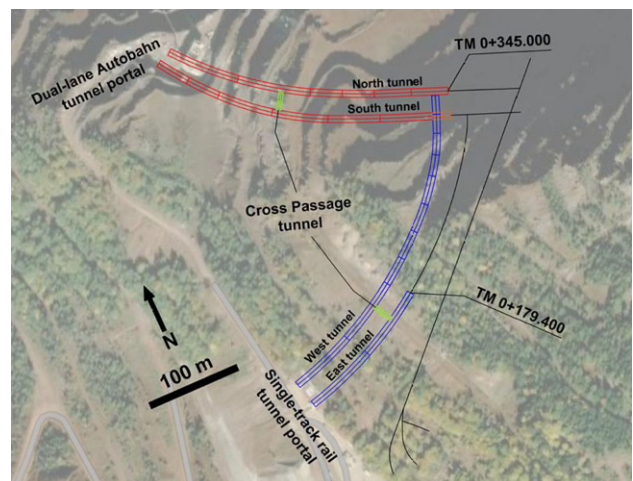


Fig. 4: Layout of ZaB. The project comprises two road tunnel tubes aligned in the West-East direction, as well as two railway tunnel tubes oriented in the north-south direction. Each of these tubes has a length of approximately 400 m. Additionally, there are two cross-passenger tubes

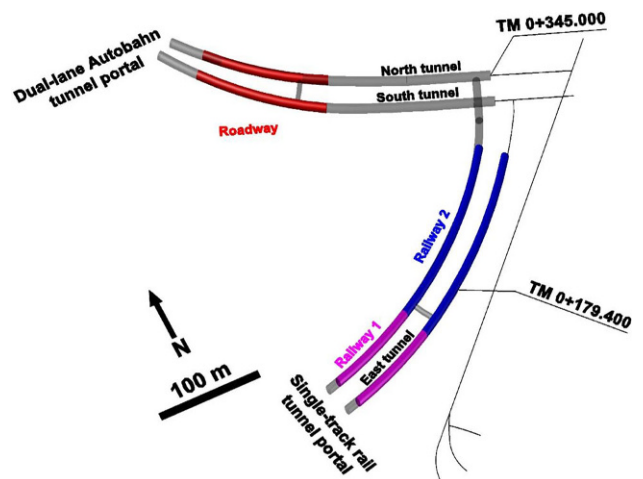


Fig. 5: Plan view of the highlighted sections encompassing Railway 1, Railway 2, and the Roadway tunnel

TABLE 1
Rock mass characteristics of each tunnel section, calculated based on data derived from the design documents [9]

Section	Rock type	Modulus of Elasticity (MPa)	Bulk Modulus (MPa)	Shear Modulus (MPa)	Joint Normal Stiffness (MPa)	Joint Shear Stiffness (MPa)
Railway 1	Blasseneck porphyry	5750	3194	2395	6388	2661
Railway 2	Blasseneck porphyry	5750	3194	2395	6388	2661
Roadway	Carbonate rock	6550	3522	2752	7277	3057

Fig. 6: Geometry and spacing of the Railway and Roadway tunnel sections, looking to the North and East for the Railway and Roadway tunnel section, respectively

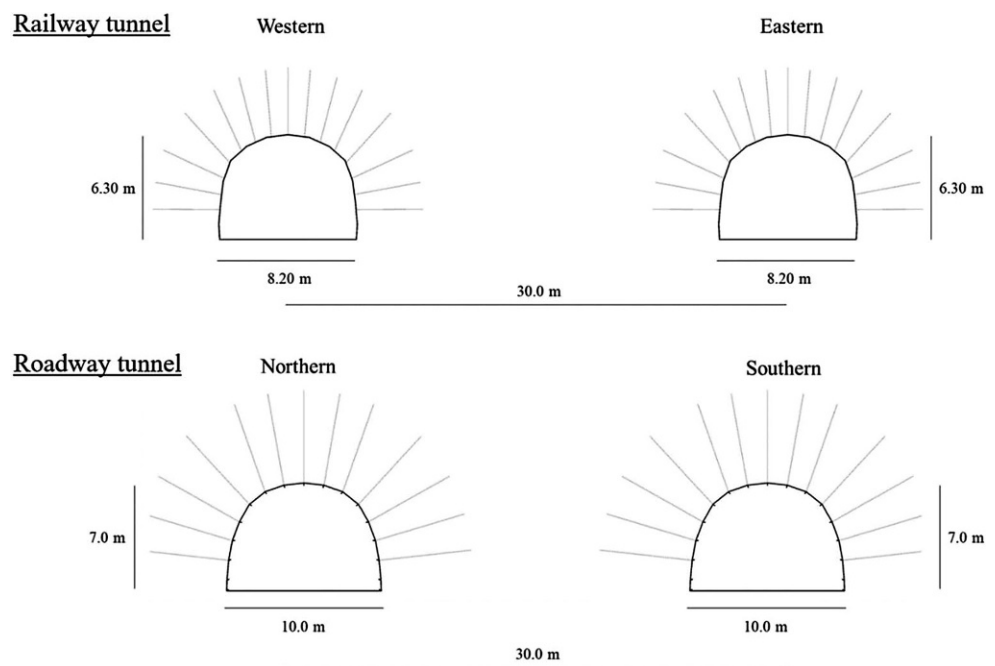
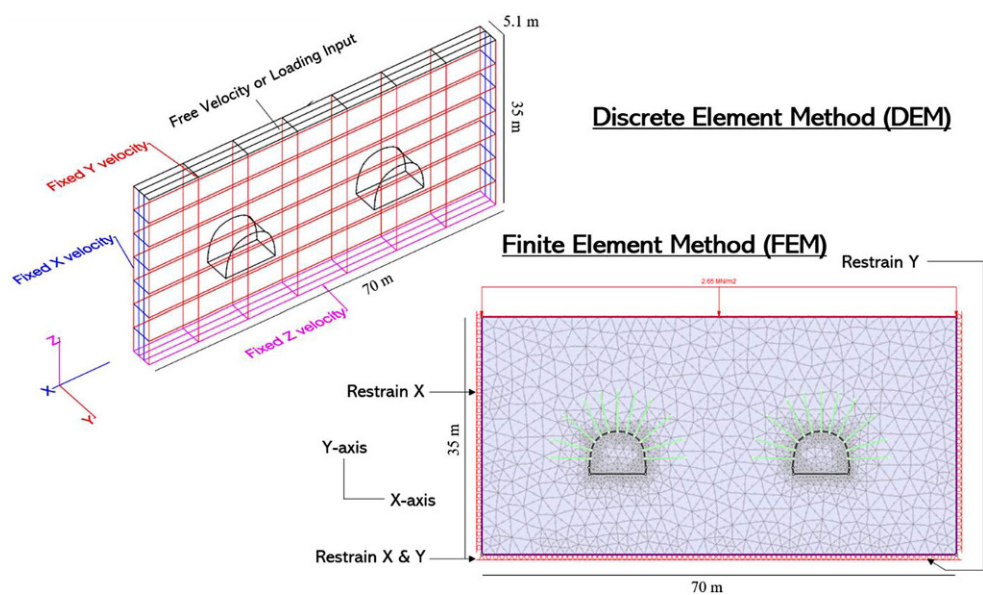


Fig. 7: Geometry of the model blocks and the boundary conditions employed in each numerical analysis method



the roadway tunnel (Fig. 5). The rock mass characteristics of each section are presented in Table 1.

4.2 Model Set-up

The railway tunnel has dimensions of 8.2m horizontally and 6.3m vertically, whereas the roadway tunnel has dimensions of 10.0m horizontally and 7.0m vertically. Both tunnels have horseshoe-shaped cross-sections, with a 30m interval for each section, as displayed in Fig. 6.

The Finite Element Method (FEM) is modeled in a 2D configuration, while the Discrete Element Method (DEM) is modeled in 3D. The DEM model block has dimensions of 70.0×35.0×5.1 m, encompassing length, height, and

width. The boundary condition is characterized by a fixed velocity in a specified axis. On the other hand, the FEM model block is sized at 70.0×35.0m in length and width. The boundary condition incorporates restraint along a specific axis (Fig. 7).

The DEM model implements rock fissures data from the geological data documentation [10] to generate a jointed rock mass model block. This is achieved through the application of the Discrete Fracture Network (DFN) module (Fig. 8), which is described by Itasca [11], resulting in an increased degree level of discontinuum within the model. The generation patterns of the joints are influenced by factors such as power-law distribution, the density of joints in specific orientations, and the range of joint lengths.

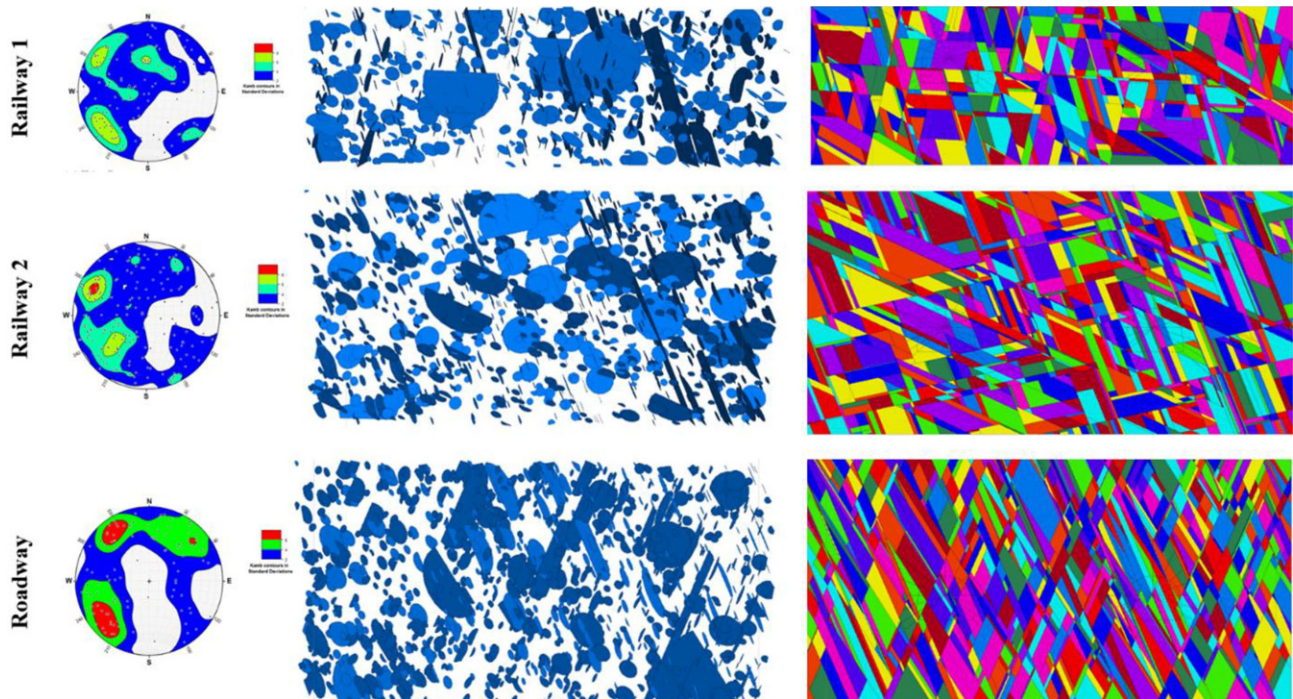


Fig. 8: Visualisation of the jointed rock mass model block generation based on fissure set data from the respective tunnel sections provided by geological data documentation [10], as represented in stereonet format

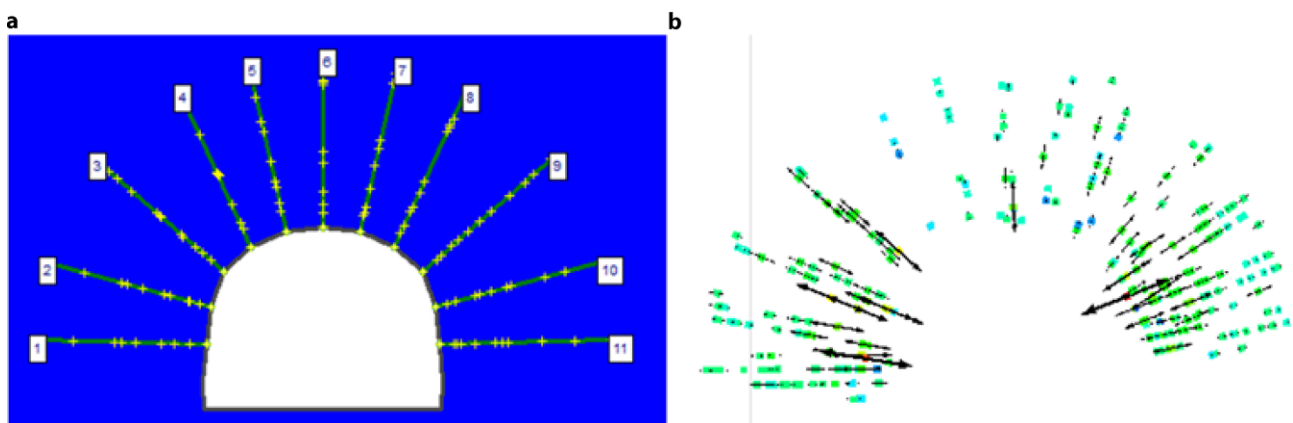


Fig. 9: Generated tensile resistance nodes in both numerical analysis methods including FEM (a) and DEM (b). These nodes facilitate the measurement of the tensile forces resulting from tunnel displacement

TABLE 2

Primary factors utilized for tunnel support in this study, calculated based on the design documentation [9]

Sections	Axial Support				Liner	
	Axial support length (m)	Tensile strength (kN)	Axial stiffness ^a (N/m/m)	Tangential/Longitudinal spacing (m)	Liner thickness (m)	Liner Modulus of Elasticity ^b (GPa)
Railway 1	4.0	250	1.5×10^8	1.0/1.0	0.25	23.8
Railway 2	6.0			1.3/1.7		
Roadway	6.0					

^aAxial stiffness calculated from Rocscience [12]

^bLiner Modulus of Elasticity calculated from Carranza-Torres and Diederichs [13]

The study incorporated tunnel relaxation, quantity, and pattern of tunnel support based on the design documentation [9]. The tunnel relaxation, defined as a time gap before tunnel support installation, was designed at approximately around 1–1.5 mm. The tunnel support system consisted of two primary variants: (1) Axial support and (2) Liner. The axial support in numerical analysis was represented as a dense set of tensile force resistance nodes, which are positioned on the axial line oriented perpendicular along the tunnel circumference (Fig. 9). On the other hand, the liner was a composite assembly involving a steel set combined with shotcrete. Table 2 provides information about the support methods employed for each tunnel section, along with the associated material properties.

4.3 Analysis Processes

The study employed FEM and DEM techniques to assess distinct construction scenarios for individual tunnel sections, incorporating the model initialisation phase. These scenarios encompassed both unsupported and supported excavation of the ground. To conduct the numerical analysis, specialized software tools were utilized: RS2 from Rocscience for FEM and 3DEC from Itasca for DEM. The procedure for numerical analysis for each method is visually illustrated in Fig. 10.

Fig. 10: Analysis procedure

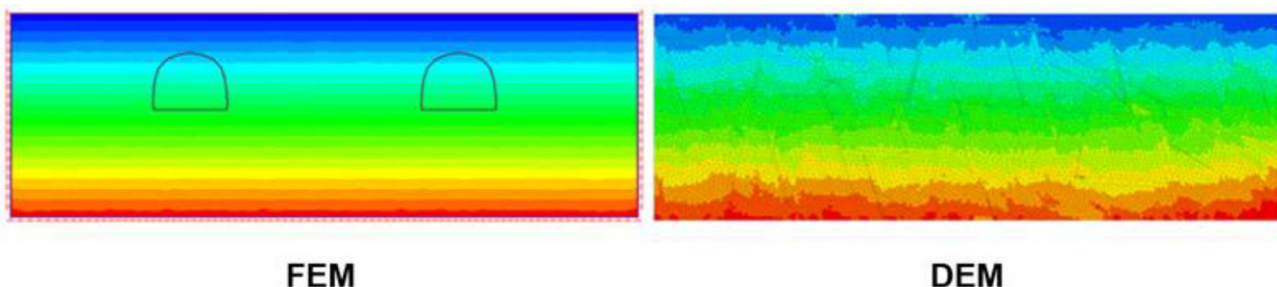
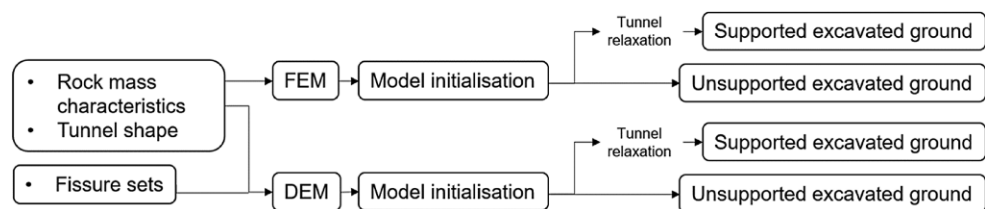


Fig. 11: Vertical stress model from FEM and DEM analysis on Railway 1 tunnel section

To prepare the FEM and DEM models for excavation, it was necessary to initialize the stresses and deformations in both models. This involved applying a vertical stress, which was determined by calculating the product of unit weight, gravity, and overburden for Railway 2 and Roadway models because of the overburden higher than the top model boundary. The methodology outlined in Brown and Hoek [14] was adopted as a reference for implementing this approach. The deformations were set to zero after the initialisation.

5. Results and Discussion

5.1 Model Initialisation

In comparing FEM and DEM (Fig. 11), it was noted that when simulating a rock mass as a continuum and discontinuum under similar overburden conditions, the magnitude of vertical stress generated at the tunnel depth level is identical. Additionally, the irregular vertical stress lines generated in the DEM model represent stress localization associated with the discontinuities.

However, when introducing an increased vertical load in the block model to simulate higher overburden conditions, as demonstrated in the Railway 2 and Roadway sections of this study, the resulting vertical stress at the tunnel

TABLE 3
Vertical stress outcome produced from model initialization phase on a particular tunnel section, alongside the input parameter values

Section	Overburden	Stress at the tunnel depth level (N/m^2)	Method	Loading input (N/m^2)
Railway 1	4 m	~12,000	FEM	None
			DEM	
Railway 2	98 m	~2,600,000	FEM	2,200,000
			DEM	2,646,000
Roadway	134 m	~3,600,000	FEM	3,080,000
			DEM	3,618,000

depth level is approximately 15% higher in FEM compared to DEM. This finding aligns with earlier research, which has indicated a variation range of 5–15% [15, 16].

According to the findings, during the model initialization phase, a 15% reduction in the loading input for FEM, as indicated in Table 3, is necessary to achieve comparable vertical stress at the tunnel depth level in both FEM and DEM.

5.2 Tunnel Displacement from Ground Excavation

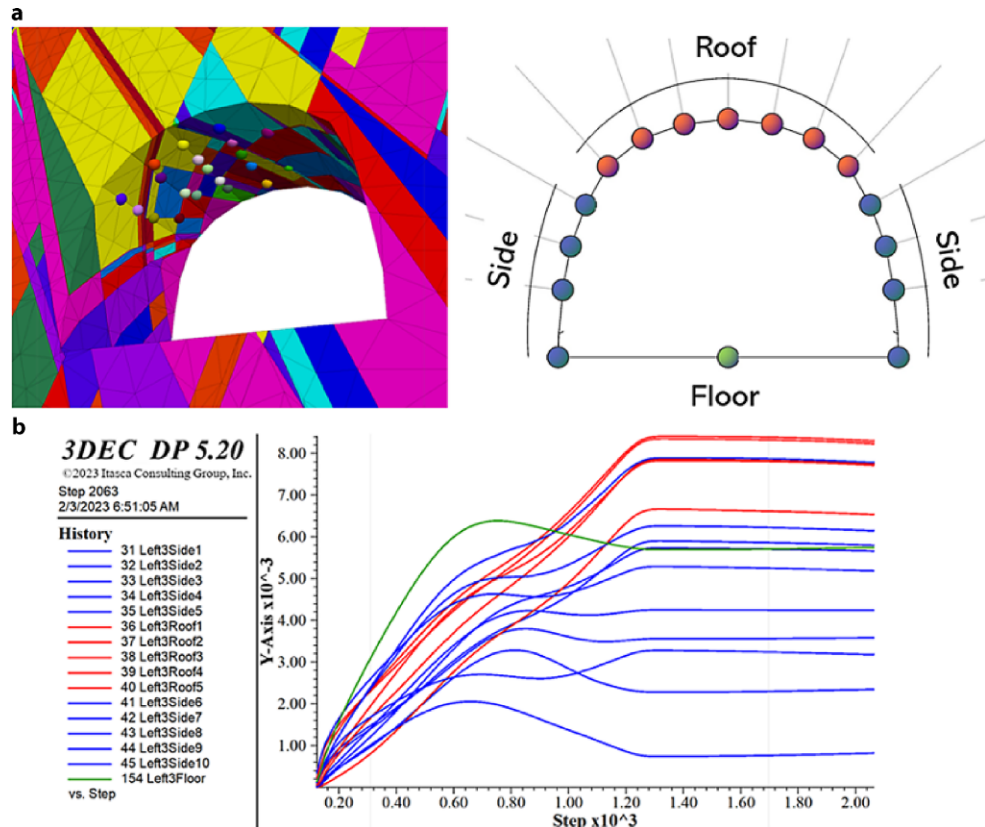
Following the excavation of the ground, the displacement of each tunnel section was assessed using observation points positioned along the tunnel circumferences on the tunnel surface (Fig. 12). The displacement data for each

tunnel section and scenario are provided in Fig. 13. All DEM model-generated displacements surpass those produced by the FEM model, with a range of 12 to 150% higher. On average, the difference amounts to approximately 46%. Furthermore, Fig. 14 demonstrates the heterogeneous distribution of deformation in the DEM model results.

5.3 Tensile Force Generation on the Axial Support

The difference between FEM and DEM model results can also be examined by observing the tensile forces along the axial support. The axial support's capacity usage, which is calculated as the percentage of the tensile force applied to the support relative to its tensile force resistance capacity, is employed in this study to facilitate demonstration and

Fig. 12: Observation points along the circumference of the tunnel surface across different sections, including the roof, side, and floor (a) showcasing displacement data obtained from these observation points (b). From these data, maximum and average displacement values can be derived



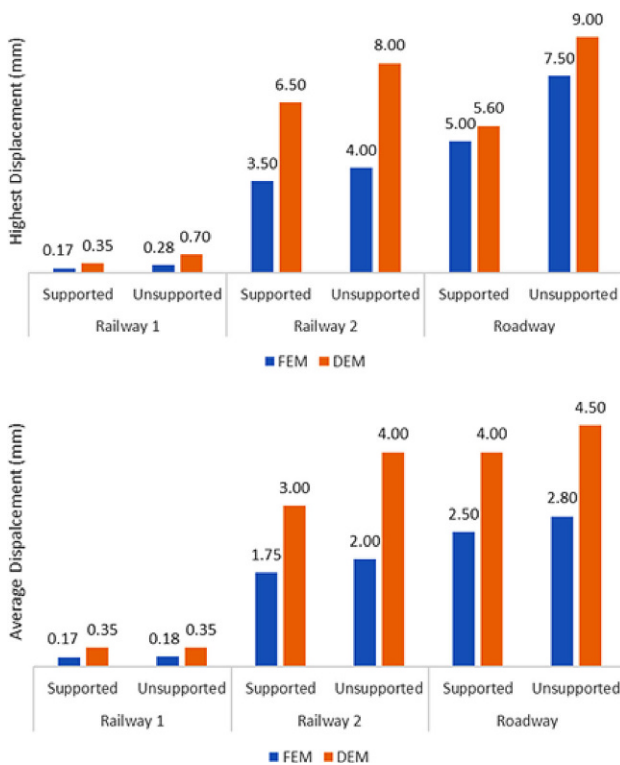


Fig. 13: A presentation of the highest and average displacement values for each tunnel section and scenario. It provides an overview of the displacements obtained from both DEM and FEM models

comprehension. The tensile force resistance of the axial support is limited to 250kN in this study. A graphical representation in Fig. 15 illustrates the capacity usages across the axial length.

It is observed that the range of capacity usage of the support in the DEM model is broader than that in the FEM model. Although a few values from the DEM model are lower than values from the FEM, the average capacity usages in the DEM model from all tunnel sections are approximately 5.5 times higher than those in the FEM model (Fig. 16). The influence of a higher magnitude of tunnel displacement in DEM analysis results in an increased tensile

force on axial support. Note that this study does not consider the impact of pre-stressing the axial support loads.

5.4 Risk Assessment Application

Using a DEM model, it is feasible to incorporate the existence of a fissure in the rock mass within the modelling process. By doing so, it becomes possible to anticipate potential events that could transpire during construction, particularly those associated with discrete geological structures present in the site area. For instance, in Railway 1 section the occurrence of wedge failure in the crown during construction has also been observed in the DEM model (Fig. 17). Additionally, asymmetric behaviour associated with heterogeneous or anisotropic rock masses can also be observed in the DEM model (Fig. 18).

6. Conclusion

In conclusion, the comparison between FEM and DEM analysis conducted on three tunnel sections at the ZaB project, considering different scenarios such as unsupported and supported excavated ground, has revealed a significant disparity in the displacement generated by both methods. Moreover, DEM analysis demonstrates a considerably higher tensile force generation on axial support, with magnitudes exceeding five times that of FEM model results. The DEM analysis also allows for the identification of events such as wedge failure and asymmetrical tunnel displacement. This study serves as an example highlighting the substantial gap between FEM and DEM modelling in fractured rock masses. Consequently, it is strongly recommended to incorporate DEM analysis in modern tunnel design in fractured rock masses to enhance understanding of tunnel behavior and facilitate risk assessment.

7. Software

In this study, computer software was utilized to examine a numerical analysis model. The software licenses em-

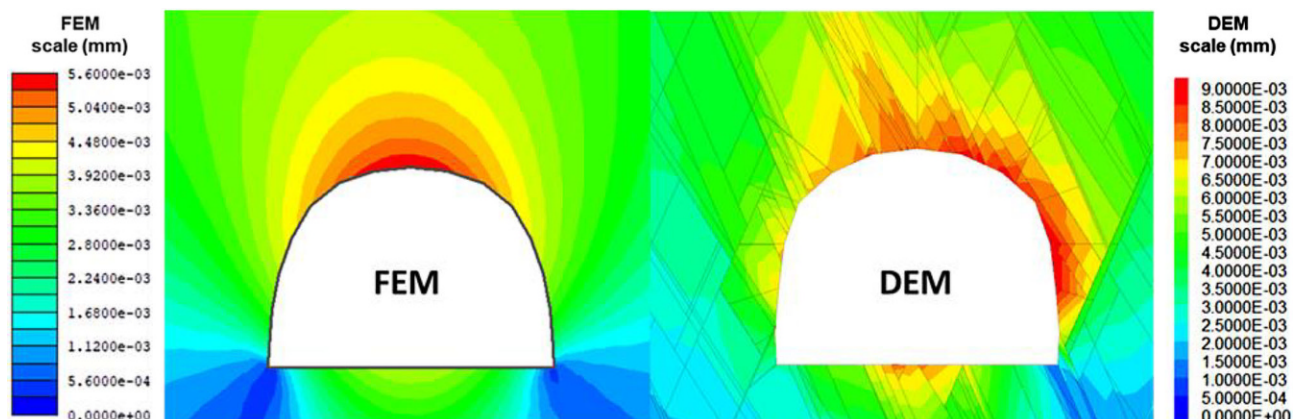


Fig. 14: Displacement model derived from the Roadway tunnel section of ZaB using DEM and FEM analysis

Fig. 15: Graphical representation of the relationship between capacity usages and axial length. The vertical axis of the graph represents the capacity usage, while the horizontal axis represents the axial length

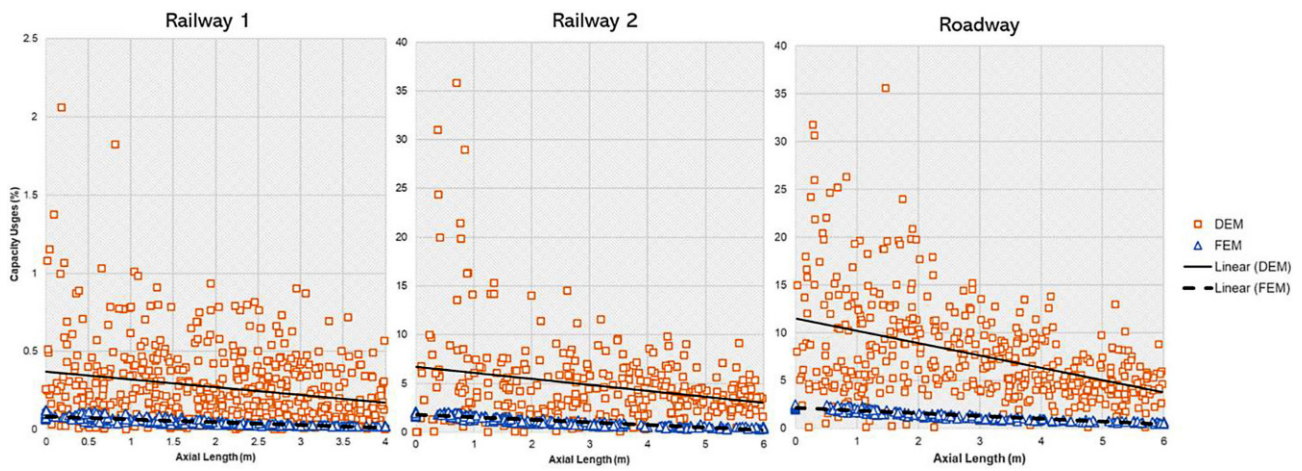
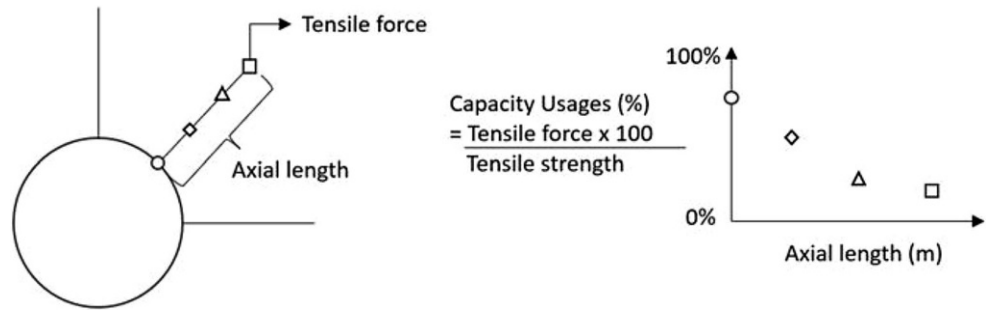


Fig. 16: Scatter plots display the capacity usages along the length of the axial support for the DEM and FEM models from all three tunnel sections

Fig. 17: Potential for wedge failure is illustrated in the DEM model. **a** The size of the potential wedge can be calculated for optimal crown support design. **b** The occurrence of the block failure incident on the Western Railway tube TM 12.5–TM 117, as documented in [10]

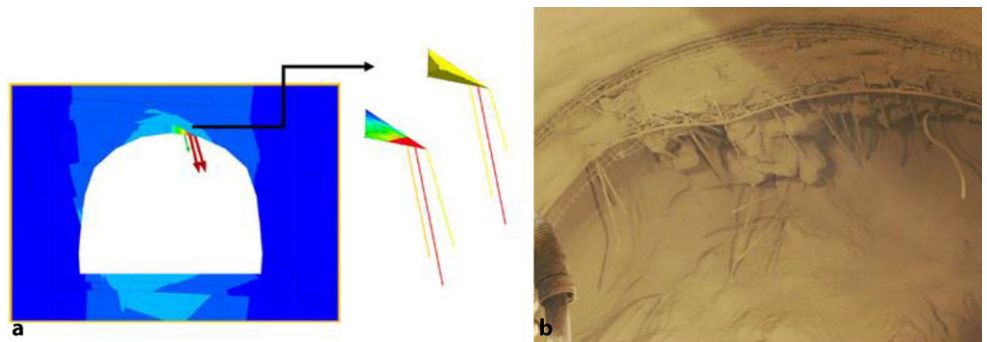
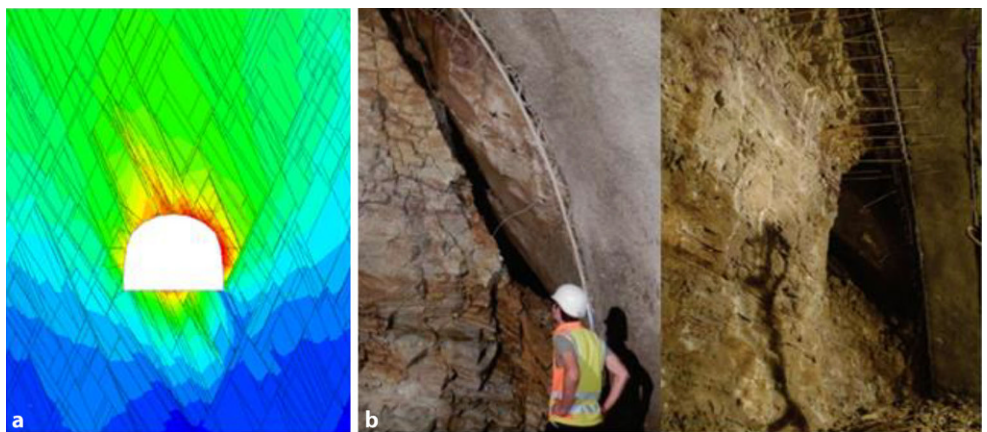


Fig. 18: Asymmetry observed in the DEM model displacements provides insight into behaviour encountered during the tunnel excavation. **a** The DEM model from Roadway section; **b** a large opening fissure reported on the Southern Roadway tube TM 51–204, as reported in [10]



ployed were the RS2 from Rocscience, obtained through the Institute of Rock Mechanic and Tunneling at Graz University of Technology, and the 3DEC from Itasca, obtained through the Department of Mining Engineering and Petroleum Engineering at Chiang Mai University.

Funding. Open access funding provided by Montanuniversität Leoben.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Rabcewicz, L.: Principles of dimensioning the supporting system for the new Austrian tunnelling method. *Water. Power* **25**, 88–93 (1973)
- Hoek, E., Brown, E.: *Pract. Estim. Rock Mass Strength* **9**(7), 80069–x (1997). <https://doi.org/10.1016/s1365-1609>
- Barton, N.H.: Shear Strength Criteria for Rock, Rock Joints, Rockfill, Interfaces and Rock Masses. In: Springer, eBooks, pp. 1–12 (2013). https://doi.org/10.1007/978-3-642-32814-5_1
- Tekkaya, A.E., Soyarslan, C.: Finite Element Method. In: Laperrière, L., Reinhart, G. (eds.) *CIRP Encyclopedia of Production Engineering*. Springer, Berlin, Heidelberg (2014) https://doi.org/10.1007/978-3-642-20617-7_16699
- Hertz, H.: On the contact of elastic solids. In: Jones, D.E., Schott, G.A. (eds.) *Miscellaneous Papers*, pp. 215–259. Macmillan and Company, (1896)
- Dorussen, B.J.A., Geers, M.G., Remmers, J.J.: A discrete element framework for the numerical analysis of particle bed-based additive manufacturing processes. *EWC* **38**(6), 4753–4768 (2022). <https://doi.org/10.1007/s00366-021-01590-6>
- Galler, R.: ZaB – Zentrum am Berg, am Steirischen Erzberg in Österreich genehmigt. *Bhm Berg- Und Hüttenmännische Monatshefte* (2014). <https://doi.org/10.1007/s00501-014-0322-5>
- Gasser, D., Gusterhuber, J., Krische, O., Pühr, B., Scheucher, L., Wagner, T., Stüwe, K.: *Geology of Styria: An overview. – Mitteilungen des naturwissenschaftlichen Vereins für. Steiermark*, vol. 139., pp. 5–36 (2009)
- University of Leoben. (n.d.). Geomechanical Design Report, Research@ZaB – Forschung im Zentrum am Berg.
- Forstinger + Stadlmann ZT GmbH. *Geol. Dokumentation, Schlussbericht*. (2019)
- Itasca Consulting Group, Inc. (n.d.). Discrete Fracture Network (DFN) – 3DEC 7.0 documentation. https://docs.itascacg.com/3dec700/common/dfn/doc/dfn_manual/dfn.html [accessed on 8 August 2023]
- Rocscience Inc. (n.d.). Swellex / Split Set. <https://www.rocscience.com/help/rs2/documentation/rs2-model/support-2/bolts/define-bolt-properties/swellex-split-set> [accessed on 8 August 2023]
- Carranza-Torres, C., Diederichs, M.: Mechanical analysis of circular liners with particular reference to composite supports. For example, liners consisting of shotcrete and steel sets. *Tunn. Undergr. Space Technol.* **24**(5), 506–532 (2009). <https://doi.org/10.1016/j.tust.2009.02.001>
- Brown, E. R., & Hoek, E. (1978). Trends in relationships between measured in-situ stresses and depth. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, **15**(4), 211–215. [https://doi.org/10.1016/0148-9062\(78\)91227-5](https://doi.org/10.1016/0148-9062(78)91227-5)
- Marzulli, V., Cisneros, L., Di Lernia, A., Windows-Yule, C.R.K., Cafaro, F., Pöschel, T.: Impact on granular bed: validation of discrete element modeling results by means of two-dimensional finite element analysis. *Granul. Matter* (2020). <https://doi.org/10.1007/s10035-019-0988-1>
- Ciantia, M.O., Arroyo, M., Calvetti, F., Gens, A.: A numerical investigation of the incremental behavior of crushable granular soils. *Num Anal Meth Geomechanics* **40**(13), 1773–1798 (2016). <https://doi.org/10.1002/nag.2503>

Publisher's Note. Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.