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A. Korobenko, M. Laforest, S. Prudhomme, R. Vaziri (Eds)

COMPUTATIONAL MODELING OF CUTTING DISC-ROCK INTERACTION IN MIXED GROUND CONDITIONS

Sahir N. Butt[1,2] **and Günther Meschke**[2]

[1] High Performance Computing, Ruhr University Bochum, Germany
sahir.butt@rub.de

[2] Institute for Structural Mechanics, Ruhr University Bochum, Germany
guenther.meschke@rub.de

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Abstract. This paper presents the performance of a simulation tool based on state-based peridynamic theory, developed to model the interaction between cutting discs of a Tunnel Boring Machine (TBM) and the ground being excavated. Compared to existing TBM performance prediction models, the current computational approach accounts for mixed ground conditions, different TBM and disc designs, as well as the direct coupling with wear models. The developed peridynamic model is thoroughly validated using several benchmarks, including indentation tests on sandstone specimens. Additionally, a full-scale Linear Cutting Machine (LCM) test conducted on Colorado Red granite is simulated, where cutting forces obtained from the computational model at various disc spacings are compared against experimental data. Excavation in mixed ground conditions, which can lead to excessive tool wear or failure due to rapidly changing cutting forces, was examined through an LCM experiment. Scaled-down peridynamic simulations show cutting force trends consistent with the LCM experiment results. Finally, to predict the influence of these varying cutting forces on tool life, an abrasive wear model is implemented in the peridynamic simulation framework.

1 INTRODUCTION

Excavation processes involving a Tunnel Boring Machine (TBM) use cutting discs to fracture and excavate rock. These cutting discs are mounted on a rotating cutterhead of the TBM, which is pressed against the tunnel face. As the cutting disc penetrates the rock, the pressure in the contact area between the disc and the rock surface increases and a crushed zone develops [1]. The stresses in this zone continue to increase, leading to the initiation of radial cracks. These cracks grow and coalesce with adjacent cracks until the rock mass is disintegrated [2]. The interaction between the rock and a cutting disc can be characterized by three-dimensional reaction forces at the disc. To accurately predict the performance of a TBM, including global thrust and torque requirements, and to design new cutter heads for specific ground geology, it is necessary to estimate the cutting forces for a single disc cutter. In addition, the loads on the disc cutters cause severe wear and damage to the tools. To plan maintenance stops and avoid unexpected TBM stoppages, it is necessary to estimate the working life of cutting tools in a given geology.

2 PERIDYNAMIC CONTINUUM

The cutting process in hard rock is modeled using an enhanced peridynamic continuum formulation [3, 4], originally presented by [5, 6]. Peridynamics allows, in contrast to standard continuum mechanics theories, for the modeling of complex fragmentation processes. The reason is, that the internal forces are computed, instead of a displacement gradient, from a displacement difference of material point $\mathbf{x}$, with a set of material points $\mathbf{x}'$ within a volume defined by a cut-off radius δ, known as the peridynamic horizon [7]. This notion of direct connectivity between the material points is referred to as a bond. Fracture processes are modeled by irreversibly deleting the bonds between the material points once they reach a critical value. Once a bond fails, it does not further contribute to the internal force calculation. In this work, the critical energy required to break a bond is calibrated using the fracture energy of the rock [8]. For a detailed overview of the models used in this work, the interested reader is referred to [4]. The open-source software Peridigm [9] was extended and used used to carry out the simulations presented in this work.

3 ROCK INDENTATION

Numerical and experimental investigations [10, 11, 12] have shown that the rock fragmentation under indentation involves several progressive deformation mechanisms including elastic deformations at the initial loading stage, then volumetric compaction, plastic deformation, and finally macro fracturing. Thus, it is necessary for a simulation model to be able to reproduce significant features observed in the indentation experiments. Peridynamic formulation [6] is modified to consider the stiffening effect observed in the experiments due to pore-collapse phenomenon observed in porous sandstone [13], for further details see [4].

Simulations performed in this work for the indentation tests cover a total of six specimen sizes, with a combination of three diameters 30, 50 and 84 mm and two heights 50 and 100 mm. For validating the current model, we use the experimental data from indentation tests on Bentheim Sandstone reported in [12]. Temporal evolution of fractures occurring due to the indentation load is presented in Figure 1 for a specimen with 30 mm diameter and 100 mm height. The simulation captures the experimental observation of the successive formation of the crushed zone and the initiation of a central macroscopic tensile fracture splitting the sample in half. Once the tensile stresses at the perimeter of this zone exceed a critical value, a tensile crack is formed which splits the specimen. As this tensile crack propagates, it exceeds a critical crack propagation velocity, at which the crack tip bifurcation takes place and the crack branches [14, 15], as shown in the fourth column of Figure 1. Finally, the specimen splits into two main and several small fragments (fifth column of Figure 1).

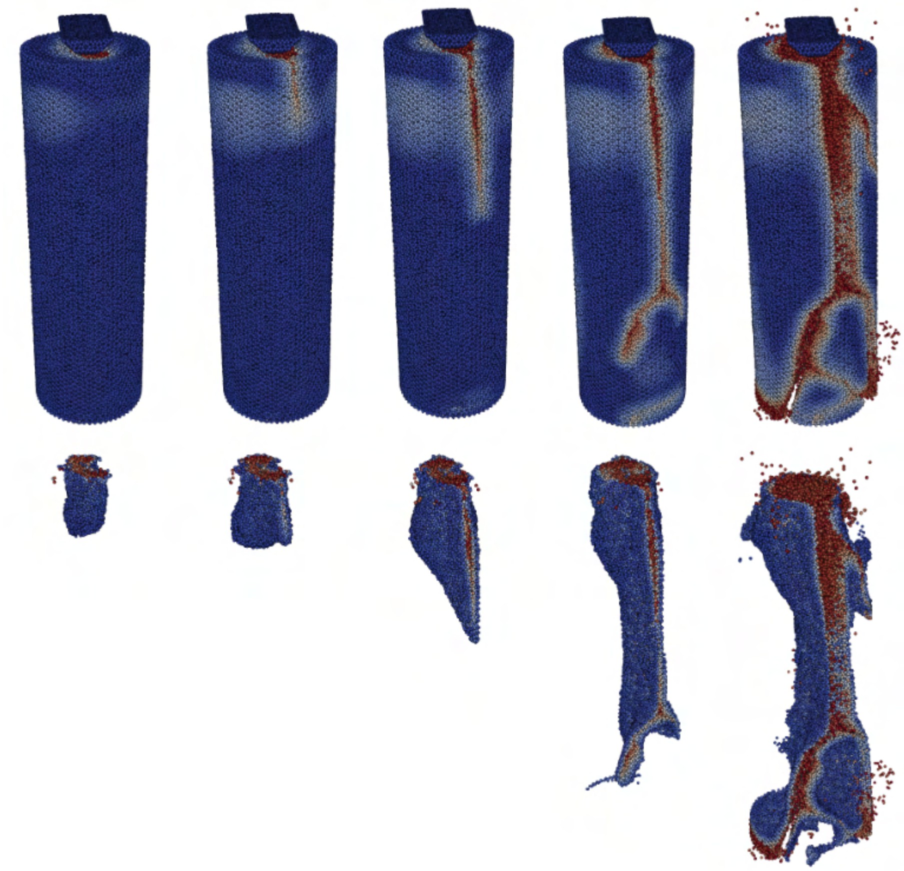

Figure 1: Temporal evolution (left to right columns) of the fracture process during the indentation test (top row), the associated damaged and cracked regions are filtered out for visualization (bottom row).

The indentation pressure resulting from the indentation loads is calculated using:

$$p = \frac{F}{4\sqrt{2R_{\text{ind}}d - d^2}\left(a_0 + \frac{d}{\tan\alpha}\right)}. \tag{1}$$

Here, F is the indentation load, d is the indentation depth, R_{ind} is the radius of the indenter tip, a_0 denotes the half width of the indenter tip, and α is the angle between the indenter and the specimen surface (here 40 °). For further details of the indenter geometry, the interested reader is referred to [12]. The indentation force-penetration and pressure-penetration relationship computed from the simulations are compared with the experimental data in Figure 2. The loading stiffness, the peak load as well as the peak indentation pressure predicted by the simulation are in a good agreement with the experiments.

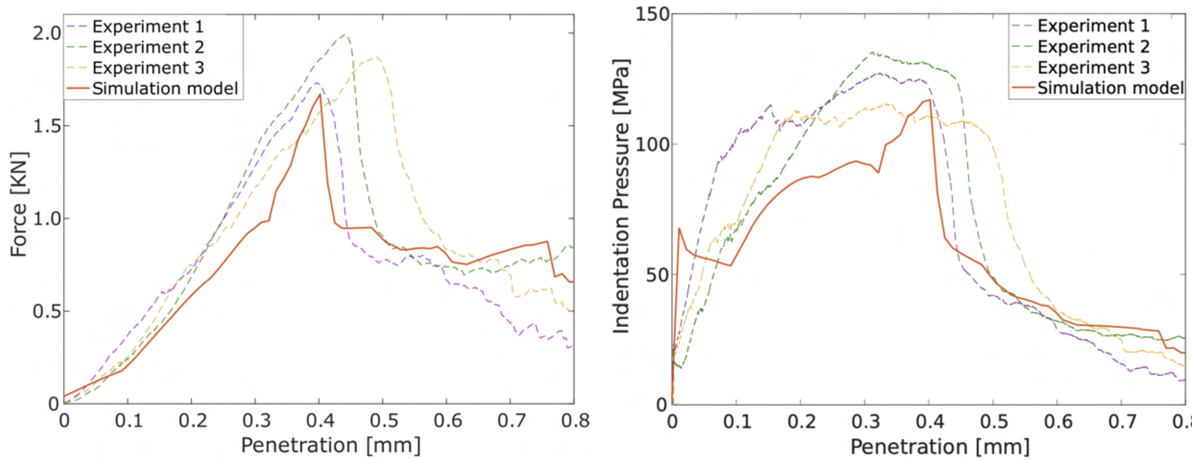

Figure 2: Comparison of the Indentation force-penetration (left) and Indentation pressure-penetration (right) relationship measured in experiments and computed from simulations.

4 LINEAR CUTTING MACHINE (LCM) TEST

LCM test [16] was developed at the Colorado School of Mines (CSM) to predict the performance of a single cutting tool. In the LCM experiment, a cutting disc moves along a rock specimen at a known penetration level and tool spacing, and tool-rock interaction is characterized by the reaction forces on the cutting disc. Several cutting lines at a fixed spacing can be performed, which comprise a cutting pass, the cutting forces can then be averaged over these cutting lines. These forces are decomposed into normal, rolling, and side forces and they are used to predict the global thrust and torque requirements for a TBM. The LCM test is a widely used experimental procedure to predict the performance of a single cutting tool [17]. This method facilitates direct measurement of the cutting forces under controlled process parameters, such as the tool penetration, spacing, and cutting speed. LCM testing is also suitable for validating rock cutting simulation models [18, 19, 20]. LCM-type simulations can be performed to predict the performance of a single cutting disc while varying different process parameters and tool geometries.

Peridynamic simulations of the LCM test carried out on Colorado red granite consider both relieved and unrelieved rock cutting cases [4]. Relieved and unrelieved rock cutting modes refer to the stress state present in the rock during the excavation process. In relieved cutting mode, the fractures initiated from the adjacent cutting tools interact with each other and relieve the stress state in the rock, resulting in lower levels of cutting forces. In contrast, in unrelieved cutting mode, the surrounding rock mass is intact and stresses are not relieved, leading to higher forces on the excavation tools. The current approach requires an initial calibration according to the pressure-dependent critical-energy model [4], in order to reproduce uniaxial tensile and compressive strengths (UTS and UCS), respectively. After calibrating UTS and UCS, simulations of the LCM test for both relieved and unrelieved cases are performed. The material parameters used for Colorado red granite are taken from [17]. The heterogeneous nature of the rock is con-

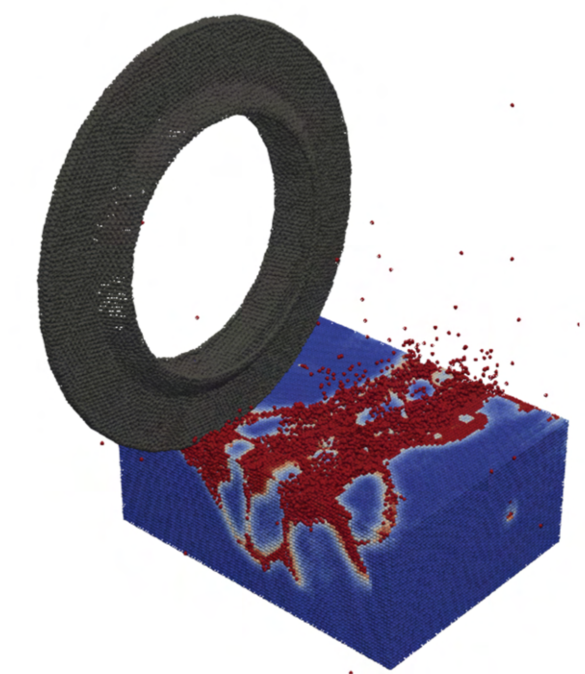

Figure 3: Simulation of the LCM test showing evolving damaged zones just before the third pass of the tool at a spacing of 76 mm and a penetration level of 7 mm.

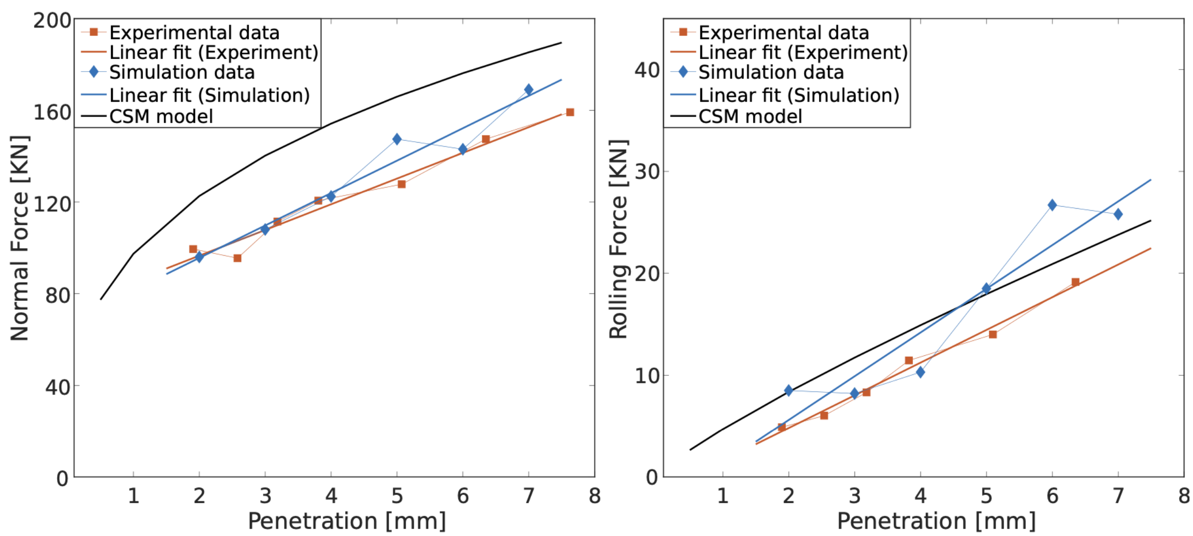

Figure 4: Average normal (left) and rolling (right) forces obtained from peridynamic simulations are compared with the CSM model and experimental data for various tool penetration levels and a tool spacing of 76 mm.

sidered using randomly distributed strength parameters, for further details the interested reader is referred to [4]. Simulations are conducted with three cutting disc passes at a fixed penetration and spacing, as shown in Figure 3. The first cutting line is used for rock conditioning to damage the rock and mimic the previous tool pass, as in the LCM test and rock cutting with a hard rock TBM cutterhead. The average cutting forces presented in this section are obtained by averaging the forces over the second and third cutting pass.

Simulation results show that the peridynamic approach can capture the chipping process and cutting forces in rock cutting simulations. For a tool penetration of 7 mm and spacing 76 mm, Figure 3 illustrates that the simulation captured the formation of rock chips between the tool passes. The average cutting forces obtained for a tool spacing of 76 mm at various penetration levels are compared with the CSM model [16] and experimental data [17] in Figure 4. The normal cutting forces are in good agreement with the experiment, while the rolling forces are slightly overestimated. As the tool spacing is reduced, the chipping process becomes inefficient, leading to lower cutting forces but also lower excavated rock mass [4].

The average cutting forces obtained from the simulations (Figure 4) exhibit some scatter due to the probabilistic nature of these simulations. As the strength parameters used to model the heterogeneous nature of the rock are randomly sampled from a Weibull distribution [3, 4], each simulation has a slightly different spatial distribution of material strength. These differences can result in the observed scatter. Ideally, a multi-simulation approach should be adapted for these cases to find an average solution. However, performing a large number of simulations with such high resolution would require a considerable computational effort and is outside the scope of the current work.

5 MIXED GROUND CONDITIONS

Mixed or heterogeneous ground conditions occur when a tunnel face has two or more layers of rock or soil with significantly different mechanical properties. Mechanized tunneling in such conditions results in highly variable loads on the cutting discs. As the cutting disc moves from soft to hard ground, an excessive load is exerted on the cutting disc at the point of contact with the hard ground layer, as shown in Figure 5 (left). The contrast of material properties at the tunnel face is replicated in an LCM experiment with a rock sample constructed using limestone and granite casted in concrete [4]. As the cutting disc moves through the various interfaces in the specimen (for e.g. concrete-granite interface) an abrupt change in the cutting forces is measured. Average normal forces obtained from four cutting passes in a LCM experiment are shown in Figure 5 (right). It can be observed that as the cutting disc moves from concrete into granite (first dotted vertical line in Figure 5, right), the cutting disc experiences an overloading which can cause abnormal wear as well as localized damage to the cutting disc.

Mixed ground conditions are simulated here using LCM tests where a cutting disc moves from soft soil into a hard rock domain. The simulations used a scaled cutting disc of 56 mm diameter and a rock specimen of $0.2\times0.15\times0.075$ m, as experimentalists have used such scaled cutting tests to facilitate the experimental setup and the availability of the apparatus in the laboratory [21]. Scaled tests were used here due to the large computational expense associated with a full-scale test. The soil material is modeled using an elastic-plastic Drucker-Prager type

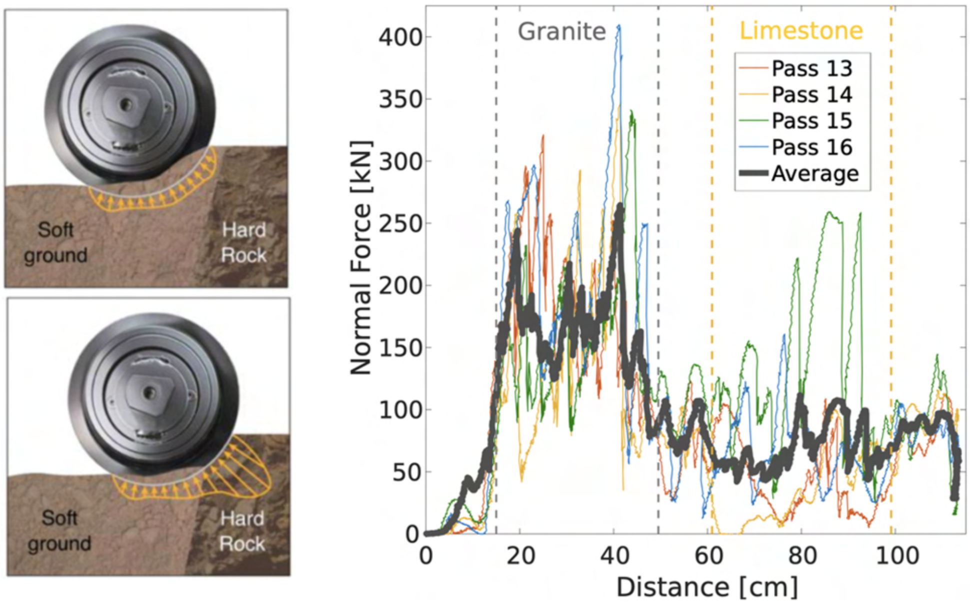

Figure 5: Schematic illustration of the forces acting on a cutting disc at a mixed face tunnel (left). Average cutting forces obtained from four cutting passes in a mixed ground LCM experiment (right).

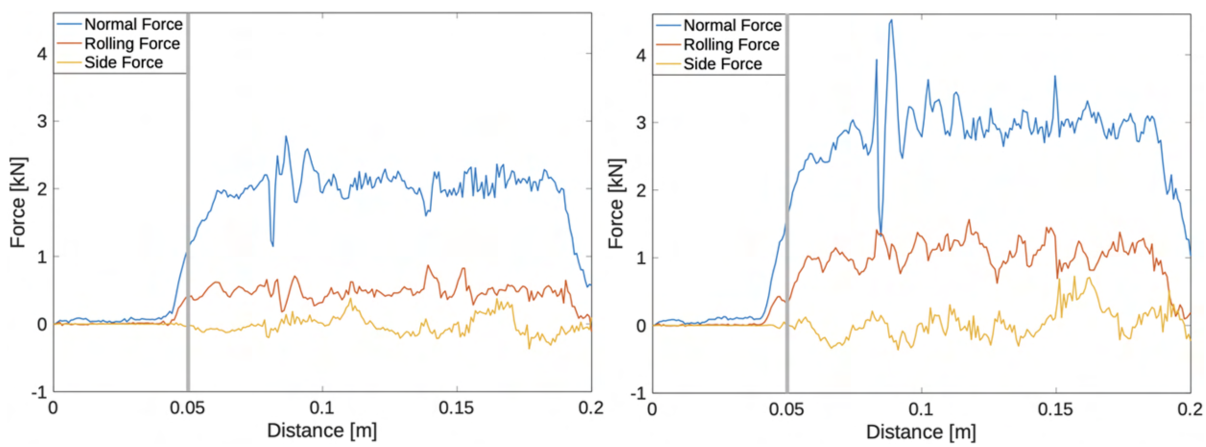

Figure 6: Cutting forces acting on a cutting disc working in mixed ground conditions (soft soil to hard rock domain) obtained from a peridynamic simulation for a penetration level of 2 mm (left) and 3 mm (right). The vertical grey line at 0.05 m cutting distance represents the soil-rock interface.

plasticity model, and the rock material is modeled using an elastic-brittle constitutive relation. The objective of these analyses is to characterize the impulse load and resulting wear on the cutting disc as it moves through the interface between two materials with significantly different mechanical properties. Such repeated impulse loads can cause excess vibration in the cutterhead

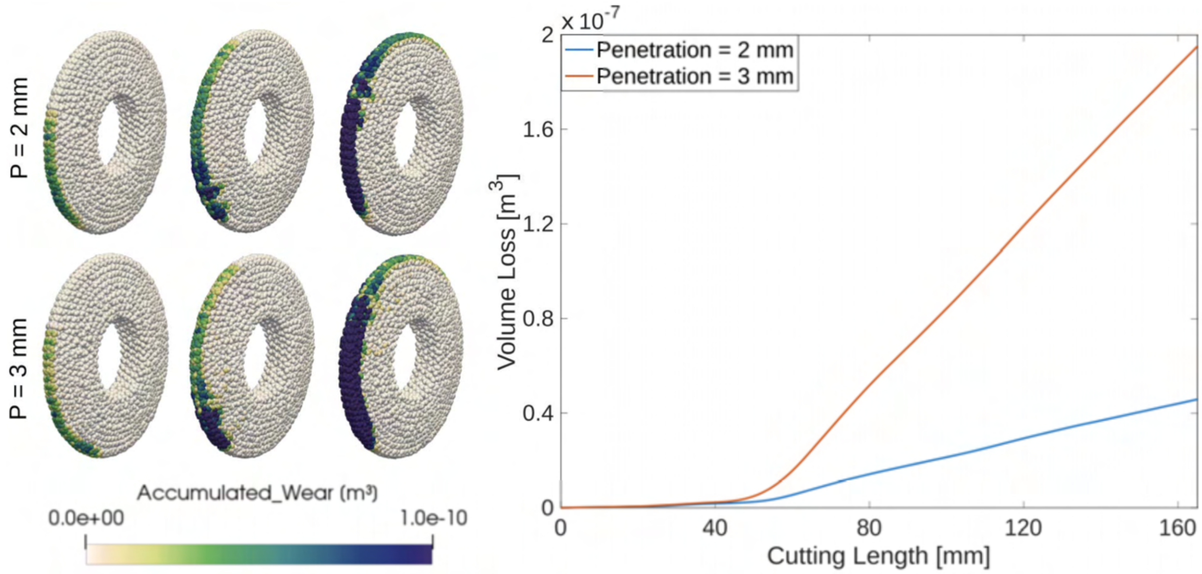

Figure 7: Comparison of the abrasive wear on the cutting disc working in mixed ground conditions at two different penetration levels (left). Total volume lost due to abrasive wear on cutting discs for the two penetration levels over the cutting length (right).

and increased fluctuations in torque and thrust of the TBM, which may ultimately result in premature damage to the cutting disc.

The reaction forces obtained fort two penetration levels (2 mm and 3 mm) are shown in Figure 6. These diagrams show that the normal cutting forces are negligible when the disc cutter is in the soil domain. However, as it reaches the soil-rock interface (cutting length = 0.05 m) and continues to move into the rock domain, the cutting forces show a peak of relatively high cutting forces. As anticipated, the comparison of cutting forces at the two penetration levels in this study shows that the peak cutting force increases proportionally with the tool penetration.

An Archard type abrasive wear model [22] has been implemented in the open-source software Peridigm. The simulation model is verified based on a simple sliding test for the abrasive wear. For further details regarding the abrasive wear model, the interested reader is referred to [4]. The verified model for abrasive wear is utilized in conjunction with the simulations for mixed ground conditions to estimate the abraded volume on the cutting discs and localized wear occurring at the soil-rock interface. Figure 7 (left) displays the accumulated wear on the cutting disc, for a 180 ° rotation, for two penetration levels at three different stages: in the soil domain (left column), at the soil-rock interface (middle column), and in the rock domain (right column). The figure reveals a significant increase in accumulated wear on the cutting disc as it progresses into the rock domain. Figure 7 (right) presents the total volume loss due to abrasive wear on the cutting disc over the cutting length for both penetration levels. A notable change in wear rate is evident as the cutting disc moves from the soil to the rock domain.

6 CONCLUSIONS

The rock indentation and excavation by means of cutting discs of a TBM has been investigated using an extended peridynamic simulation model. The simulation results for the indentation tests obtained using the extended model were validated through comparison with force-penetration and pressure-penetration data from experiments performed on Bentheim sandstone samples of various sizes. The simulation technique was further validated by simulating LCM tests on granite samples while considering the rock material heterogeneity through random sampling of strength parameters from a Weibull distribution. The cutting forces were found to be in good agreement with the experimental data and the CSM model predictions. In addition, the simulation model was used to perform LCM tests for mixed ground conditions where the cutting disc moves from a soil medium, modeled using a Drucker-Prager type plasticity model, to a hard rock medium. An Archard-type wear law was incorporated in the simulation model to simulate abrasive wear of the cutting discs. The mixed ground simulations revealed an abrupt increase in the cutting forces as the disc moves from soil to rock medium, resulting in uneven wear of the cutting disc. These results demonstrated the effectiveness of the proposed method in accurately identifying the cutting forces on the cutting discs working in changing ground conditions. The extended simulation model has a promising potential for modeling the rock excavation process in various scenarios.

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REFERENCES

[1] Jamal Rostami. Study of pressure distribution within the crushed zone in the contact area between rock and disc cutters. *International Journal of Rock Mechanics and Mining Sciences*, 57:172–186, 2013.

[2] Jung-Woo Cho, Seokwon Jeon, Sang-Hwa Yu, and Soo-Ho Chang. Optimum spacing of tbm disc cutters: A numerical simulation using the three-dimensional dynamic fracturing method. *Tunnelling and Underground Space Technology*, 25(3):230–244, 2010.

[3] Sahir N. Butt and Günther Meschke. Peridynamic simulations of rock indentation. *PAMM*, 23(4):e202300051, 2023.

[4] Sahir N. Butt. *Computational Fracture and Fragmentation Modeling using Peridynamics: Application to Mechanized Excavation in Hard Rock*. PhD thesis, Ruhr University Bochum, 2023.

[5] Stewart A Silling. Reformulation of elasticity theory for discontinuities and long-range forces. *Journal of the Mechanics and Physics of Solids*, 48(1):175–209, 2000.

[6] Stewart A Silling, M Epton, O Weckner, J Xu, and E Askari. Peridynamic states and constitutive modeling. *Journal of Elasticity*, 88(2):151–184, 2007.

[7] Sahir N. Butt, J.J. Timothy, and G. Meschke. Wave dispersion and propagation in state-based peridynamics. *Computational Mechanics*, 60(5):725–738, 2017.

[8] John T Foster, Stewart A Silling, and Weinong Chen. An energy based failure criterion for use with peridynamic states. *International Journal for Multiscale Computational Engineering*, 9(6), 2011.

[9] Michael L Parks, David J Littlewood, John A Mitchell, and Stewart A Silling. Peridigm users'guide v1. 0.0. Technical report, Sandia National Laboratories, 2012.

[10] P. A. Lindqvist, H. H. Lai, and O. Alm. Indentation fracture development in rock continuously observed with a scanning electron microscope. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 21(4):165–182, 1984.

[11] Haiying Huang and Emmanuel Detournay. Discrete element modeling of tool-rock interaction ii: rock indentation. *International Journal for Numerical and Analytical Methods in Geomechanics*, 37(13):1930–1947, 2013.

[12] Hongwei Yang, Jörg Renner, Lukas Brackmann, and Arne Röttger. Normal indentation of rock specimens with a blunt tool: role of specimen size and indenter geometry. *Rock Mechanics and Rock Engineering*, 2022.

[13] Emmanuelle Klein, Patrick Baud, Thierry Reuschlé, and TF Wong. Mechanical behaviour and failure mode of bentheim sandstone under triaxial compression. *Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy*, 26(1-2):21–25, 2001.

[14] Sahir N. Butt and G. Meschke. Peridynamic analysis of dynamic fracture: influence of peridynamic horizon, dimensionality and specimen size. *Computational Mechanics*, 67(6):1719–1745, Jun 2021.

[15] Sahir N. Butt and G. Meschke. A rate-dependent damage model for prediction of high-speed cracks. *Proceedings in Applied Mathematics and Mechanics (PAMM)*, 2018.

[16] Jamal Rostami. *Development of a force estimation model for rock fragmentation with disc cutters through theoretical modeling and physical measurement of crushed zone pressure*. PhD thesis, 1997.

[17] R Gertsch, L Gertsch, and Jamal Rostami. Disc cutting tests in colorado red granite: Implications for tbm performance prediction. *International Journal of rock mechanics and mining sciences*, 44(2):238–246, 2007.

[18] Sahir N. Butt and G. Meschke. A 3d peridynamic model of rock cutting with tbm disc cutters. In M. von Scheven, M. Keip, and N. Karajan, editors, *Proceedings of the 7th GACM Colloquium on Computational Mechanics for Young Scientists from Academia and Industry*, pages 752–755, Stuttgart, Germany, 2017. Institute for Structural Mechanics, University of Stuttgart.

[19] Jung-Woo Cho, Seokwon Jeon, Ho-Young Jeong, and Soo-Ho Chang. Evaluation of cutting efficiency during tbm disc cutter excavation within a korean granitic rock using linear-cutting-machine testing and photogrammetric measurement. *Tunnelling and Underground Space Technology*, 35:37–54, 2013.

[20] Carlos Labra, Jerzy Rojek, and Eugenio Oñate. Discrete/finite element modelling of rock cutting with a tbm disc cutter. *Rock Mechanics and Rock Engineering*, 50(3):621–638, 2017.

[21] Martin Entacher, Stefan Lorenz, and Robert Galler. Tunnel boring machine performance prediction with scaled rock cutting tests. *International Journal of Rock Mechanics and Mining Sciences*, 70:450–459, 2014.

[22] JeFoa Archard. Contact and rubbing of flat surfaces. *Journal of applied physics*, 24(8):981–988, 1953.