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Study of the effect of penetration depth and disc speed on cutting forces using LS-DYNA simulations

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ABSTRACT: The forces imparted upon cutting discs represent crucial design parameters for tunnel boring machines (TBMs) engaged in rock excavation processes. These forces comprise normal and rolling forces, which are influenced by factors including penetration depth, spacing, and linear and rotational velocity of the disc. Therefore, a careful examination of these forces is necessary for the design of effective TBMs. Linear cutting tests are time-consuming and financially prohibitive exercises. Consequently, precision numerical simulations can serve as a suitable alternative approach. In this report, the LS-DYNA software environment was employed to conduct simulations validating two constitutive models of concrete behavior: Johnson Holmquist (JHC) and RHT. The impact of variables such as penetration depth, and linear and rotational motion of the disc on exerted forces was investigated. The findings indicate penetration depth notably impacts both normal and rolling forces. Augmenting depth from 2.5mm to 7.6mm results in escalations of normal force from 96kN to 159kN and rolling force from 6.1kN to 22.5kN. As linear and rotational velocities of discs increase, forces decrease marginally. However, elevating linear speed from 0.33mm to 1.65mm precipitates merely a 13% reduction in normal force (from 155kN to 175kN) and 5% decrease in rolling force (from 20.6kN to 19.5kN), according to the results obtained.

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1- Introduction

Tunnel boring machines (TBMs) have been extensively implemented in tunnel development for objectives such as roadways and subway systems. The design of the cutter head is one of the principal and crucial aspects influencing production efficacy. Head diameter, disc quantity, normal force, rolling force, penetration depth, and disc spacing are pivotal parameters in drilling head engineering.

Meanwhile, normal forces, appropriate disc interval, and penetration profundity principally sway shearer disc effectiveness as reported by prior studies [1]. The cutting disc acts as the primary tool employed by full-face TBMs for rock fragmentation. Hence, analyzing vertical and rolling pressures on the disc is imperative for optimizing the machine cutter head configuration and enhancing excavation productivity.

Several researchers have digitally replicated rock excavation via TBMs using numerical modelling. As per existing literature, the primary aim of this article is to explore penetration depth and linear and rotational velocity impacts on normal and rolling pressures imparted to discs. Simulation was accomplished using the finite element technique via LS-DYNA software, offering advantages over conducting physical linear cuts including reduced time and cost requirements, unnecessary repetition avoidance upon parameter modification, and generalizability to all disc and rock types.

2- Simulation

The simulated rock sample measured 500 mm and comprised 1,500,000 discrete cubic elements each 2 mm in size. As shown in Figure 1, confinement conditions governing the linear rock cutting test developed by Gertsch et al. were replicated numerically, limiting rock movement from both sides and base. These boundary restrictions, defined experimentally and computationally, prevented specimen shifts induced by disc cutter application of force.

LS-DYNA supports several finite element techniques for dynamical modeling. The Smoothed Particle Hydrodynamics (SPH) and Lagrangian methods could be applied. Although the SPH solver enables a more precise and natural solution than Lagrangian, its vast computational demands necessitate a highly capable system and significantly prolong solution time. An additional complexity concerns generating suitable boundary conditions given SPH's dispersed spherical particle formulation - careful control is required to avoid inter-penetration diminishing accuracy. Owing to these considerations regarding SPH implementation detailed, the present analysis implemented solely Lagrangian dynamics to

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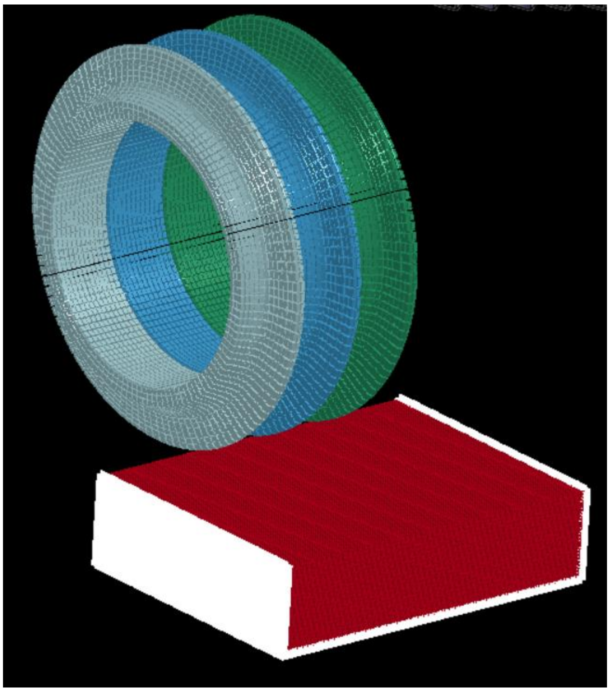

Fig. 1. A view of the rock with three discs and boundary conditions governing the problem

simulate linear rock cutting.

3- Results and Discussion

To validate the numerical modeling approach and quantify simulation error, three simulations were conducted mirroring the linear cutting tests detailed by Gertsch et al. By comparing computational outcomes against experimental measurements, the accuracy and reliability of the finite element analysis could be confirmed. Quantifying any divergence between simulation and experiment is crucial for verifying the suitability of the model framework and solution methodology in reliably replicating real-world rock- cutting dynamics. This validation process thereby gives confidence that the parameter investigation can provide insights with Meaningful technical relevance [2]:

- Rock strength: 158 MPa
- Disc rotation speed: 0.0015 radians/ms
- Disc linear cutting speed: 0.33 mm/ms
- Penetration depth: 2.5, 1.5 and 7.6 mm
- Spacing: 76 mm

The experimental observations of Gertsch et al. conformed with simulations conducted at diverse speeds, both showing that heightened penetration depth augments normal force. This affirms the findings of Roxborough and Phillips [3], Hyun Lee [4], and Gertsch et al [5].

Crucially, simulations revealed normal pressures on disc and rock declined when velocity multiplied fivefold relative to baseline, corroborating a direct relationship between this

Table 1. The difference percentage of linear cutting simulation results and the experiments' results by Gertsch et al

Penetration (mm)	% Normal force error	% Rolling force error
2.5	-1.33	20.98
5.1	-0.70	-19.14
7.6	-2.52	-8.44

reduction and depth increase - approximating 13% at 7.6mm depth, 9% at 1.5mm, and 3% at 2.5mm. Results implied forces respond marginally to velocities exceeding fivefold acceleration.

Basic regression review of the association between the parameter of interest (normal/rolling force) and influencing factor (depth) at various speeds validated prior linear cut and computational investigations. Greater depths consistently elevated force magnitudes across all three velocities.

Equation 1 quantifies the empirically determined relationship between normal force and depth for single, fivefold, and tenfold velocities. This numerical representation provides useful design guidance to engineers regarding expected disc pressures over a range of operational conditions.

The validity of simulations was thus confirmed by their alignment with open-air trials and existing literature, showcasing LS-DYNA's capacity for practically simulating rock-cutting mechanics.

$$FN = 74.93 - 1.054V + 10.569P \qquad R^2 = 0.97 \quad (1)$$

4- Conclusions

This paper investigates the variation in normal and rolling forces on discs through simulations conducted using the LS-DYNA software environment with the Lagrangian solution method. Colorado red granite, with a uniaxial compressive strength of 158 MPa, is modeled. The analysis reveals that the aforementioned forces are highly sensitive to changes in penetration depth. An increase in depth from 2.5mm to 7.6mm leads to a 40% rise in normal forces and a 72% increase in rolling forces. When speed is augmented from the base rate to 5 times it, reductions of 3% and 13% are observed in normal force for depths of 2.5mm and 7.6mm respectively. The corresponding decreases are 4% and 16% for a 10-fold speed rise.

Rolling forces vary by -5% and +1% for a 5 times speed boost, and -8% and +0.5% with a 10 times boost. This demonstrates that speed has less than 10% influence on vertical and rolling forces below 7.6mm depth and under 20% impact at 7.6mm. Rather than elevating speed to lessen disc loads, the study recommends focusing on disc geometry, normal force, optimal penetration depth, and other impactful parameters. The high accuracy obtained in simulating linear rock cutting by shearing discs using LS-DYNA affirms the software's viability, contingent upon meticulous initial modeling for validation purposes. Correct selection of solution methodology, material behavior constitutive model, and associated parameters is crucial to derive outputs of reliable precision.

Finally, a relationship for estimating normal forces is presented using polynomial regression analysis accounting for penetration depth and velocity.

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