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Numerical Investigation of the Soil-Screw Conveyor Interaction

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ABSTRACT

Earth Pressure Balance (EPB) shield Tunneling Boring Machines (TBMs) are widely used for excavating tunnels, where controlling soil stability and managing discharge rates using screw conveyor are critical for efficient operation. Although various large-deformation numerical techniques have been proposed to simulate soil discharge in EPB TBMs, many suffer from high computational cost. Understanding the soil-screw interaction remains critical for optimizing discharge control and operational stability. This study applies the Coupled Eulerian-Lagrangian (CEL) method in ABAQUS to evaluate soil discharge and torque, two key parameters for EPB TBM operation. Experimental discharge data and torque measurements were used to validate the numerical model. The proposed coulomb friction coefficients yield simulation results that closely match the experimental soil discharge rates and torque values, demonstrating the reliability of the model under tunneling operation conditions. The CEL-based approach proves effective for predicting critical screw conveyor behavior, offering a computationally validated framework for performance analysis in tunneling applications.

1. INTRODUCTION

Earth Pressure Balance (EPB) shield Tunnel Boring Machines (TBMs) are extensively used for tunneling in urban soft ground due to their ability to maintain face stability and control ground movement. A key component in EPB operation is the screw conveyor, which regulates the discharge of excavated soil (or muck) from the pressurized chamber to atmospheric pressure. Proper control of excavated soil discharge rate is essential for maintaining face support, optimizing excavation rate, and

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preventing surface settlements or face collapse.

Numerous experimental and numerical studies have aimed to simulate and understand the soil discharge behavior through screw conveyors. Merritt and Mair (2006, 2008) conducted systematic model tests and developed theoretical models describing pressure gradient and torque based on interface shear stresses and screw geometry. Lee and Kwon (2023) employed Discrete Element Method (DEM) simulations calibrated with physical experiments to examine the influence of particle shape, screw pitch, and inclination on discharge behavior of spherical and chip-type rock particles. Other researchers such as Jin et al. (2023) and Talebi et al. (2015) have explored the rheological effects of conditioned soil in screw conveyors using CFD, showing the importance of wall slip effects and yield stress in maintaining pressure gradient and avoiding muck spewing.

However, high computational cost and limitations in capturing the particle–structure interaction at large deformations remain challenges in current modeling approaches. In this context, the Coupled Eulerian-Lagrangian (CEL) method offers a promising solution by enabling robust simulation of soil–screw interaction with large deformations and complex boundary contact conditions. This study utilizes the CEL method in ABAQUS to simulate the soil discharge process and quantify discharge rates and torque, both critical for optimizing EPB TBM performance.

2. NUMERICAL SIMULATION

2.1 The Coupled Eulerian–Lagrangian (CEL) method

The CEL method combines the advantages of the Lagrangian and Eulerian approaches to simulate large-deformation problems with contact. In CEL, structures are modeled with Lagrangian elements, while deformable media are defined in an Eulerian domain. The governing equations are solved using an operator split (Lagrangian and Eulerian phase) as shown in Eqs. (1) and (2) (Wang et al., 2015).

$$\frac{\partial f}{\partial t} = S \tag{1}$$

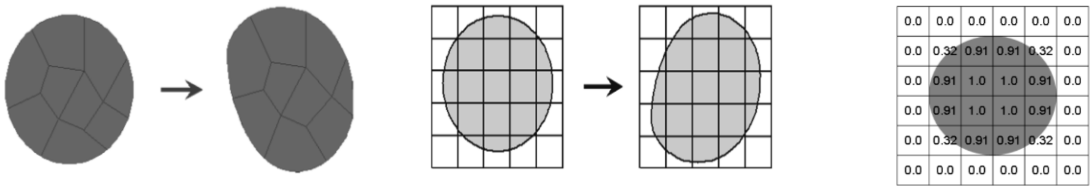
$$\frac{\partial f}{\partial t} + \nabla \cdot \phi = 0 \tag{2}$$

where f represents the field variable, ϕ is the flux function, and S is the source term.

Each Eulerian element maintains a volume fraction (EVF), indicating the proportion of the element filled by a specific material (from 0 to 1). Contact between Lagrangian and Eulerian bodies is enforced via the penalty method. The distribution of materials during the analysis can be visualized through a contour plot of the EVF variable, as illustrated in Fig. 1

2.2 CEL model

A 3D CEL model was developed using ABAQUS/Explicit to simulate the soil discharge process in a screw conveyor system, replicating the experimental setup proposed by Merritt (2006; 2008). The numerical domain and loading conditions closely followed the physical configuration shown in Fig. 2



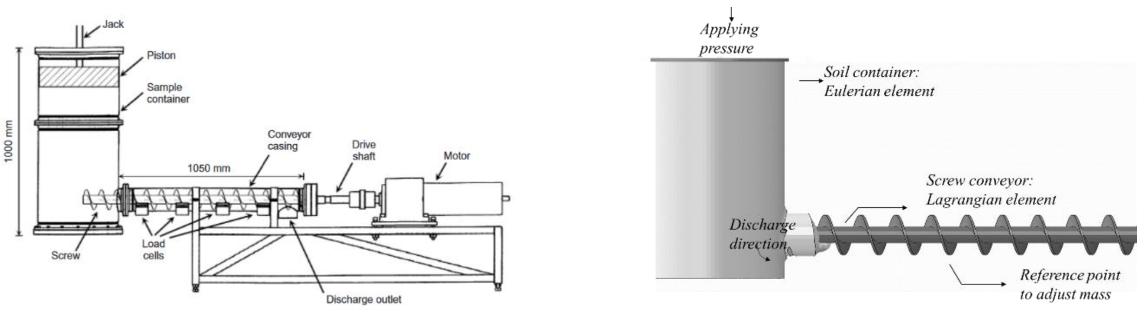
(a) Lagrangian analysis (b) Eulerian analysis (c) Eulerian volume fraction

Fig. 1 Schematic of deformation of CEL analysis.

The Eulerian domain represents the soil container (Φ 420 mm × 1000 mm), while the screw conveyor as Lagrangian rigid body is 1200 mm long with a flight diameter of 102 mm, shaft diameter of 43 mm, and pitch of 80 mm.

The soil was modeled using the Mohr-Coulomb failure criterion under undrained conditions. Material properties were assigned based on experimental data from Merritt (2006;2008), as summarized in Table 1. The EVF was set to 1.0 in the pre-filled region of the Eulerian domain.

General contact was used to define interaction between the soil and screw. In the normal direction, hard contact was applied, while in the shear direction, Coulomb friction (CF) was defined with friction coefficients of 0.2, 0.5, and 0.8. Simulations were performed at screw rotation speeds of 5, 15, and 25 rpm. Key output variables included discharge volume and discharge rate.



(a) Experimental set-up (b) Numerical set-up

Fig. 2 Experimental set-up and numerical set-up (Merritt, 2006;2008)

Table 1. Parameter of numerical set-up

Parameter	*Value*	*Unit*	*Parameter*	*Value*	*Unit*
Soft soil (London clay)			*Soil container and Screw conveyor*		
Unit weight	*17*	*kN/m³*	*Container internal diameter*	*420*	*mm*
Young's modulus	*6.8*	*MPa*	*Container height*	*1000*	*mm*
Poisson's ratio	*0.49*	*-*	*Piston diameter*	*420*	*mm*
Cohesion	*7*	*kPa*	*Conveyor casing length*	*1000*	*mm*
			Screw length	*1200*	*mm*
			Screw shaft diameter	*43*	*mm*
			Screw pitch	*80*	*mm*

Data from experimental study by Merritt. (2006;2008)

2.3 Simulation results

Fig. 3 presents the discharge volume over time for three rotational speeds at a constant friction coefficient of 0.5. The results show that discharge volume increases almost linearly with time, and higher rotational speeds yield higher discharge volumes.

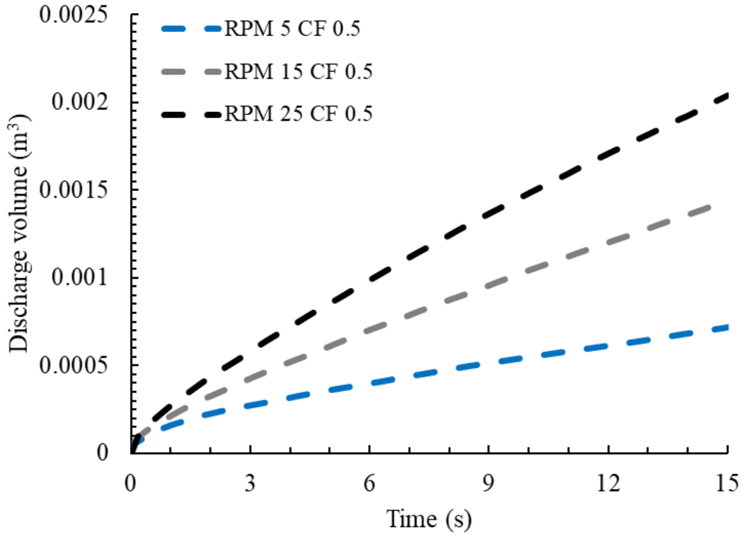


Fig. 3 Discharge volume results

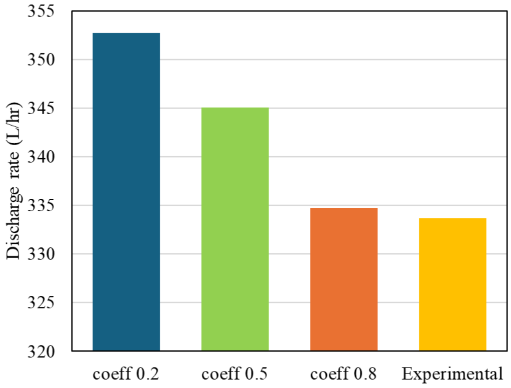
3. CONCLUSIONS

Fig. 4 summarize the discharge rates (in L/h) computed as the slopes of the volume–time curves, compared against experimental results. These comparisons were made for friction coefficients of 0.2, 0.5, and 0.8 at each rpm setting. As the screw speed increases, the overall discharge rate also increases across all cases.

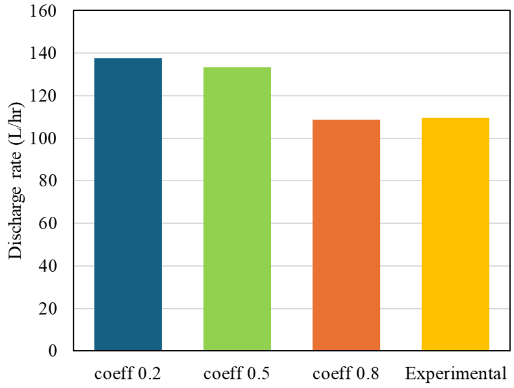
The simulation results reveal that the discharge rate is sensitive to the CF coefficient between the soil and screw. For all rotational speeds, increasing the CF coefficient from 0.2 to 0.8 led to a noticeable reduction in discharge rate. This trend is attributed to greater shear resistance at the contact interface, which reduces soil mobility along the screw flights.

When compared to the experimental data, the simulation results with a CF coefficient of 0.8 consistently showed the closest agreement. This implies that a coefficient of 0.8 most accurately reflects the actual soil–metal interaction under the tested conditions. Lower friction values tend to overestimate discharge, likely due to unrealistically low shear resistance at the interface.

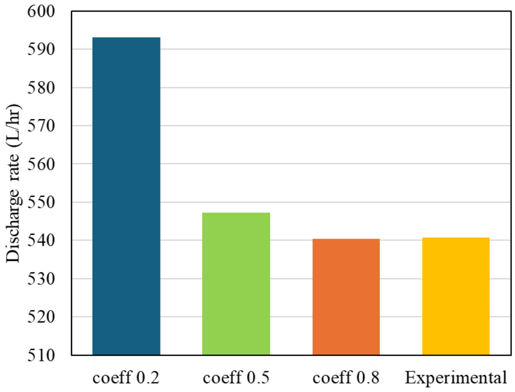
These findings suggest that careful calibration of the CF coefficient is essential for reliable prediction of discharge performance in CEL-based screw conveyor simulations.



(a) Case 1 - RPM 5



(b) Case 2 - RPM 15



(c) Case 3 – RPM 25

Fig. 4 Discharge rate results

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