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Design and development of an EPB shield machine for the geotechnical centrifuge

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ABSTRACT: The rapid expansion of urban rail transit has intensified the demand for tunnelling in close proximity to existing infrastructure, creating significant challenges for maintaining ground stability and protecting adjacent structures in densely built environments. Centrifuge modelling has proven to be an effective tool for investigating tunnelling processes and ground responses; however, most existing simulators oversimplify soil-machine interactions and operational processes. To overcome these limitations, a novel miniature earth pressure balance (EPB) shield machine has been developed with a 150 mm cutterhead diameter, featuring independent control of shield advancement, cutterhead rotation, and soil discharge via three separate motors. The model EPB machine is designed to operate at up to 80g and enables the study of prototype tunnels ranging from 2.5 m to 10 m in diameter. The developed simulator demonstrates the ability to realistically reproduce EPB tunnelling mechanisms under in-situ geostress, offering valuable physical insights into cutterhead and chamber pressure design and assessing ground deformation in mechanised tunnelling projects.

1 INTRODUCTION

Earth Pressure Balance (EPB) Tunnel Boring Machines (TBMs) are widely used for tunnelling in soft and mixed ground conditions, particularly in urban environments where strict control of face stability and ground deformation is required. By maintaining a controlled pressure within the excavation chamber, EPB machines are able to balance in-situ stresses at the tunnel face, thereby limiting ground loss and surface settlement. Despite their extensive application in practice, EPB tunnelling remains a complex process. Field experience and monitoring data from full-scale projects show that excavation performance and ground response are highly sensitive to operational parameters such as cutterhead rotation speed, advance rate, penetration per revolution, and screw conveyor discharge (Chen et al. 2026). However, the influence of these parameters is difficult to isolate in the field due to geological variability, operational constraints, and the limited possibility of performing controlled experiments at prototype scale.

Geotechnical centrifuge modelling offers an effective experimental framework to investigate tunnelling processes under scaled stress conditions. When combined with suitably designed tunnelling simulators, centrifuge tests allow systematic investigation of excavation mechanisms in a controlled and repeatable manner. Nevertheless, many existing centrifuge-based TBM models adopt simplified kinematic concepts or neglecting realistic control of excavation chamber pressure. These simplifications restrict their ability to reproduce true EPB operational behaviour.

To address these limitations, a novel miniature EPB machine has been designed at the SHORES Research Centre, New York University Abu Dhabi. The EPB machine features independent control of cutterhead rotation, shield advancement, and screw conveyor discharge for investigating face stability, chamber pressure control, and ground deformation.

2 CENTRIFUGE MODELLING OF EPB SHIELD MACHINE

Geotechnical centrifuge modelling enables the investigation of tunnelling mechanisms under correctly scaled stress conditions by increasing the gravitational acceleration acting on a reduced-scale physical model. Under a gravity level of Ng, stresses within the soil mass are preserved while geometric dimensions scale by 1/N, allowing realistic simulation of prototype ground stress response. This approach is particularly well suited for studying mechanized tunnelling, where face stability and ground deformation are strongly governed by stress-dependent soil behaviour.

In the context of EPB tunnelling, centrifuge modelling offers the additional advantage of enabling controlled investigation of the interaction between excavation processes and chamber pressure regulation. The developed miniature EPB machine (Figure 1) is designed to operate in a large beam centrifuge at gravity levels up to 80g, allowing simulation of prototype tunnel diameters ranging from approximately 2.5 m to 10 m. The model is mounted within a rigid strongbox (1230×450×800 mm) that provides structural support and ensures reliable boundary conditions during centrifuge flight, as shown in Figure 1.

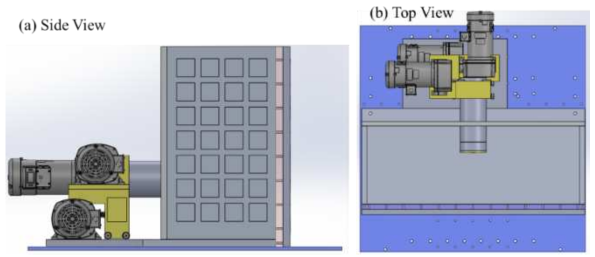

Figure 1. Conceptual layout of the developed EPB machine.

The centrifuge testing framework enables systematic variation of operational parameters such as advance rate, cutterhead rotation speed, penetration per revolution, and discharge rate while maintaining constant in-situ stress conditions. Instrumentation includes chamber pressure sensors, displacement sensors, and monitoring of mechanical indicators such as motor current or torque. Together, these measurements allow direct assessment of pressure evolution, face stability, and ground deformation mechanisms during tunnelling conditions.

3 DESIGN METHODOLOGY

Model-scale cutterhead torque requirements are derived from scaled prototype face pressures typically ranging from 150 to 250 kPa. Nominal torque demand lies within approximately 10-20 N·m, with higher values possible under adverse cutting conditions. Motor selection, therefore, incorporates conservative safety margins, and continuous monitoring of torque or current is used to identify overload or jamming. Shield advancement is achieved using a lead-screw-driven linear actuator capable of delivering advance rates consistent with centrifuge scaling. Soil discharge is regulated using an independently driven miniature screw conveyor, with helix geometry selected to allow precise control of discharge rate. Chamber pressure is regulated indirectly through volume balance, with screw conveyor speed serving as the primary control variable and advance rate acting as a secondary adjustment. The modular cutterhead design permits different cutting tool configurations, facilitating evaluation of behavior across soil types. Table 1 depicts the technical details of the developed EPB shield machine.

Table 1. Technical specifications of the developed EPB shield machine.

Parameter	Typical range
Design g-level	80
Max. cutterhead speed	10 rpm
Max. advance speed	10 mm/min
Electric motor capacity	0.5 hp
Max. travel	300 mm
Max. chamber pressure	300 kPa
Max. thrust force	20 kN
Control philosophy	Multi-mode operation

A human-machine interface provides real-time feedback on pressure, kinematic variables, and mechanical indicators, enabling manual and pressure-assisted operation with clearly defined safety limits.

4 CONCLUSIONS

A novel miniature EPB TBM has been developed for geotechnical centrifuge modelling, addressing key limitations of previous tunnelling simulators. The system enables independent control of cutterhead rotation, shield advancement, and soil discharge while adhering to centrifuge scaling principles. The design integrates realistic mechanical capacity, modular construction, instrumentation, and a pressure-based operational framework.

The developed EPB TBM provides a robust experimental platform for investigating face stability, pressure control strategies, and soil-machine interaction in mechanized tunnelling, supporting both fundamental research and validation of numerical models.

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