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Real-time unsupervised monitoring of earth pressure balance shield-induced sinkholes in mixed-face ground conditions via convolutional variational autoencoders

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ABSTRACT

This study introduces a real-time unsupervised monitoring framework for monitoring sinkhole formation events during earth pressure balance (EPB) shield tunneling operations. A feature extractor (FE) is constructed by coupling variational Autoencoders structure with convolutional neural network layers (VAE-CNN) to manage the complexity of EPB operational data, including non-linearity and temporal dependencies. The monitoring framework consists of two main phases: offline modeling and online monitoring. In the offline modeling phase, an FE model is trained using data-intensive techniques to define a subspace characterizing the behavior of multivariate data without sinkhole formations. The squared prediction error (*SPE*) statistics and the control limits are computed for detection. During the online monitoring phase, unseen EPB data is propagated to generate *SPE* values and determine sinkhole events based on whether these values surpass the control limit. Sensor validity index violation counts were used to isolate the most influential variables, while the results demonstrated the superiority of the proposed VAE-CNN method, achieving a 100% detection rate and a 0.9% false alarm rate. The influential variables identified include cutter resolutions per minute, jack speed, screw pressure, torque, and cutter seal components. The monitoring system shows great potential for early warnings during EPB operations to mitigate sinkhole formation risks.

1. Introduction

The intensified urbanization and population growth witnessed in the past century have given rise to diverse urban needs, especially in urban infrastructure and effective transportation development. As cities expand, essential elements such as bridges, interchanges, roads, roundabouts, highways, and tunnels have become significant (Qiao and Huang, 2022). Tunneling, a significant process in transportation, strategic projects, and resource exploitation, has played a crucial role in advancements like subway transportation, hydroelectric plant construction, and underground mining (Pourhashemi et al., 2022).

With the rapid development of these infrastructures, tunnel boring machines (TBM) have been broadly utilized and preferred for tunnel construction due to their advantageous operations, as they execute closed-mode maneuvers that enhance safety measures by ensuring the stability of the surrounding rock mass (Huang et al., 2022). This involves utilizing instant support with concrete linings and mitigating the risks associated with groundwater pressure under the water table (Lee et al., 2021). Furthermore, shield tunneling operations are known for their efficiency, cost-effectiveness, and environmental friendliness (Ayawah et al., 2022).

Earth pressure balance (EPB) machines are shield TBM designed to function in soft ground conditions, water pressure, high water table, karstic, and sedimentary environments (Wan et al., 2024). During EPB

Abbreviations: *AE*, Autoencoders; *CNN*, Convolutional neural networks; *DR*, Detection rate; *EPB*, Earth pressure balance; *FAR*, False alarm rate; *H*, Hurst exponent; *KDE*, Kernel density estimator; *LSTM*, Long short-term memory; *MDR*, Misdetection rate; *PCA*, Principal component analysis; *PM*, Process monitoring; *RNN*, Recurrent neural networks; *R/S*, Rescaled range analysis; *SVI*, Sensor validity index; *SPE*, Squared prediction error; *t-SNE*, t-distributed stochastic neighbor embedding; *TBM*, Tunnel boring machine; *VAE*, Variational autoencoders; *ELBO*, Variational lower bound.

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