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Adaptive adjustment strategy for earth pressure balance (EPB) operation parameters for pre-control of shield tunneling-induced surface settlement: a case study

Key words:

Pre-control of settlement; Optimization and inversion; Multi-head self-attention; Long short-term memory; Random forest algorithm

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Challenges in EPB Shield Parameter Control

The ground subsidence caused by shield tunneling poses a significant safety hazard to surrounding buildings and pipelines.

The existing "full-parameter optimization" strategies typically treat all parameters as independent variables for exhaustive search, ignoring the inherent synergy and physical coupling relationships among the parameters (such as the interaction between thrust, cutterhead torque and support pressure).

This leads to the fact that the theoretical optimization results cannot be implemented in actual engineering, with uncontrollable parameters experiencing significant fluctuations and the pre-control effect being poor.

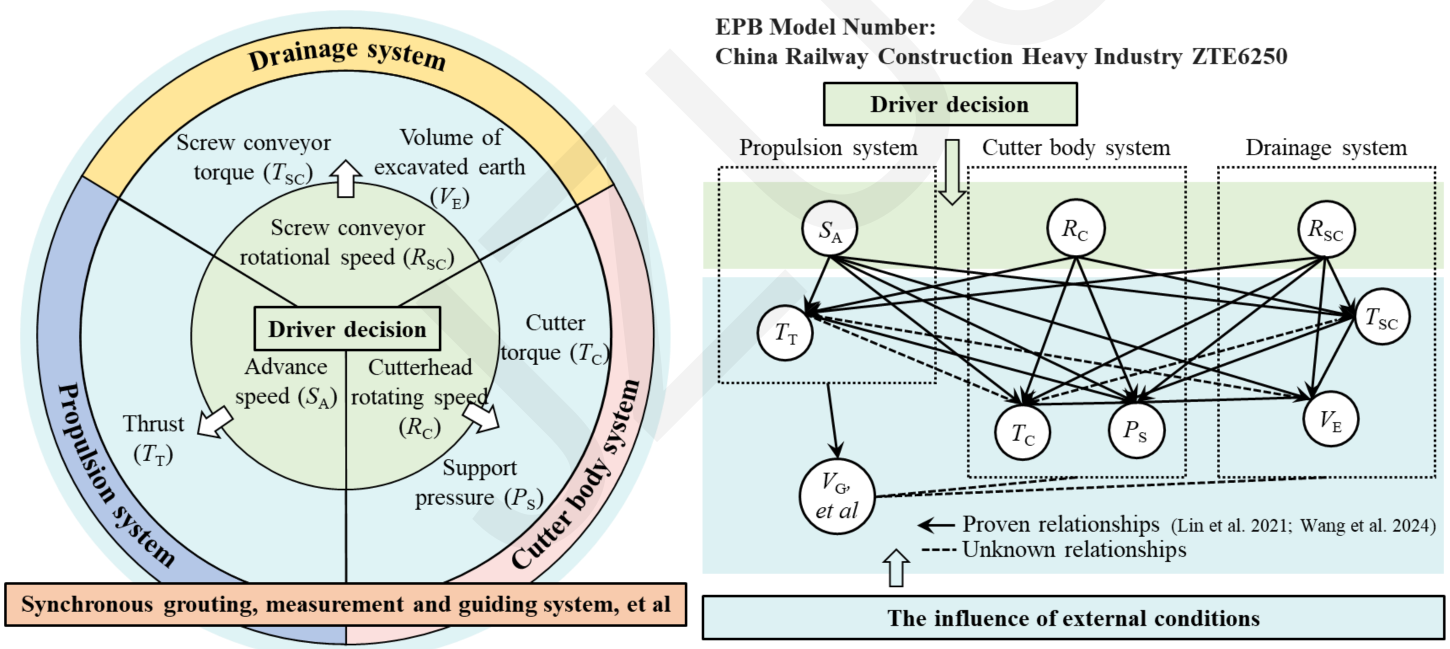

Fig. S2 System relations and interaction topology of parameters in an EPB shield

Lin CJ, Yang XD, Gong YJ, et al., 2021. Prediction Model of In-chamber Earth Pressure for EPB Shield Based on PSO-BP and Parameter Sensitivity Analysis of Tunneling Parameters. Journal of Basic Science and Engineering, 29(5):1220-1233.

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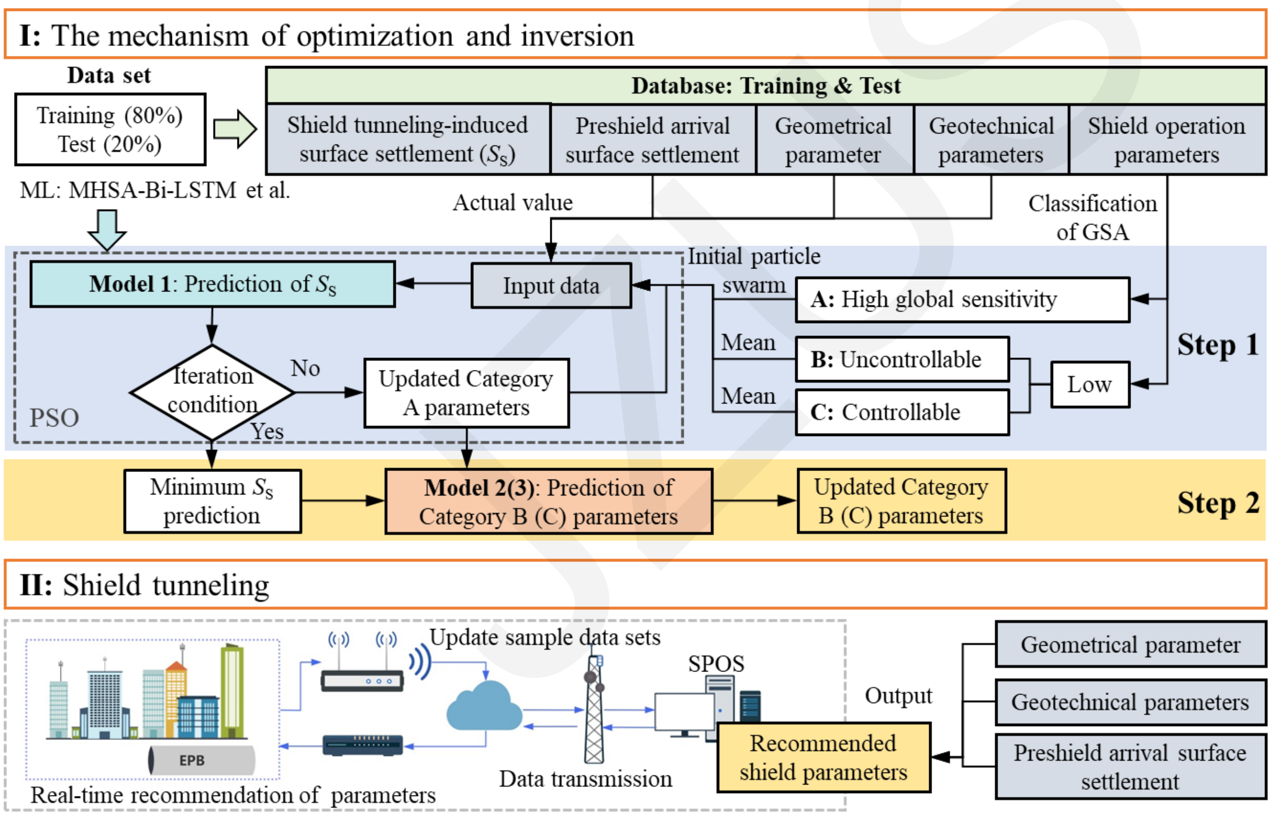
Core Innovation: An Integrated Optimization-Inversion Strategy

Transition from blind optimization of all parameters to adaptive adjustment based on sensitivity classification.

Based on the global sensitivity analysis of Sobol, the running parameters are classified into three categories:

- **Category A (High sensitivity):** Directly use the PSO algorithm for forward optimization.
- **Category B & C (Low sensitivity):** Use the random forest (RF) for inverse prediction, maintaining the physical coordination among parameters.



- While effectively reducing settlement, minimize the damage to the inherent mechanical transmission laws of the shield machine to the greatest extent.

Fig. 2 Schematic diagram of the self-adaptation method of EPB shield tunneling

MHSA-Bi-LSTM Settlement Prediction Model

Spatiotemporal Dependency: The data generated during shield tunneling exhibits strong temporal and spatial sequence characteristics.

Model Architecture: A deep learning model integrating multi-head self-attention mechanism (MHSA) and bidirectional long short-term memory network (Bi-LSTM) was constructed.

Advantage:

Bi-LSTM enhances the memory retention capability for long time series.

The MHSA mechanism can extract key data features in parallel from multiple subspaces, accurately capturing the dynamic nonlinear mappings under complex geological conditions.

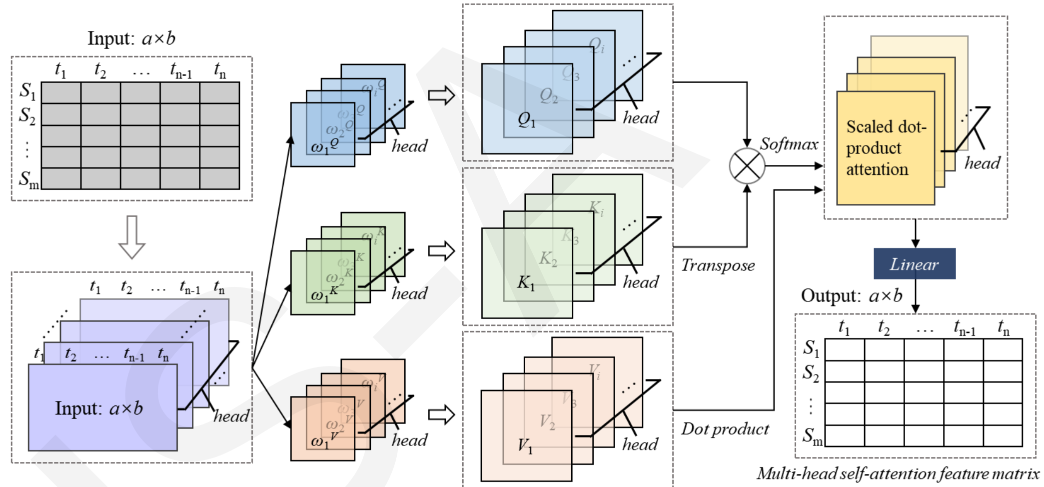


Fig. S5 The principle of the MHSA mechanism

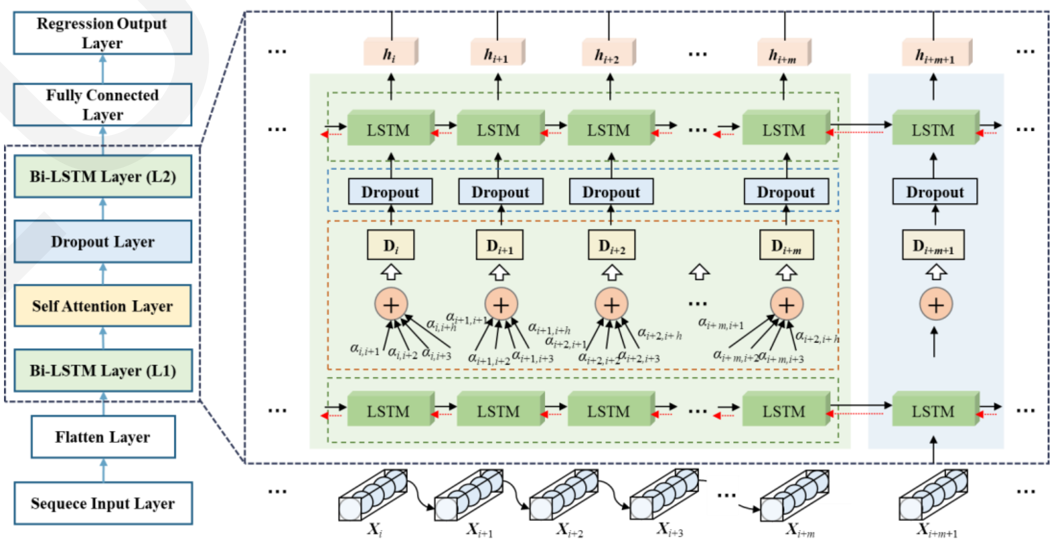


Fig. S8 The architecture of MHSA-Bi-LSTM model

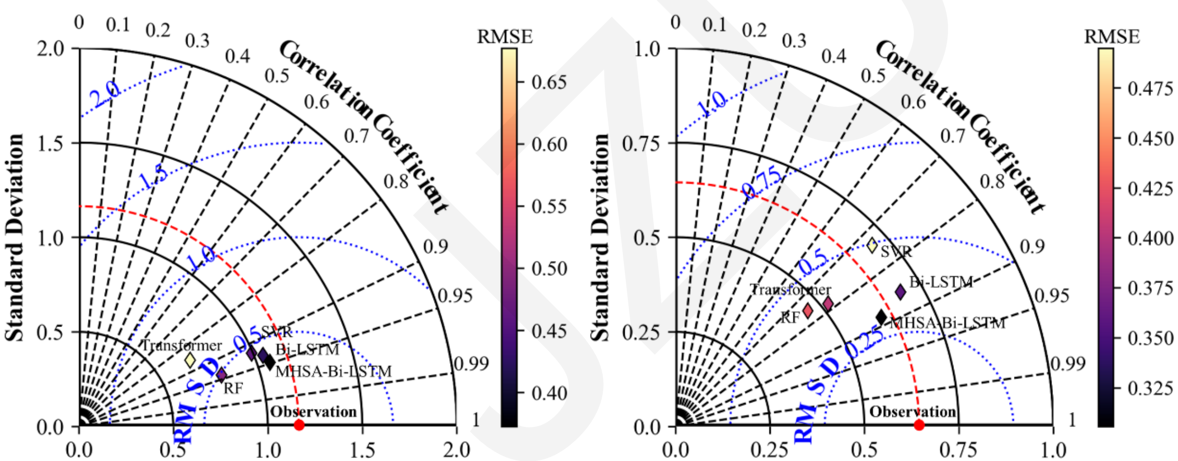
High-Fidelity Settlement Prediction

Compared and analyzed SVR, RF, Transformer, Bi-LSTM and MHSA-Bi-LSTM comprehensively.

Results:

- MHSA-Bi-LSTM performed the best on the test set:
  - ✓ MAE = 0.283,
  - ✓ RMSE = 0.352,
  - ✓ R^2 = 0.78.
- The prediction error of 85% of the samples was controlled within 10%.

The high-precision meta-model provides a reliable fitness function for subsequent parameter



(a) Training & validation sets

(b) Test set

Fig. 6 Standard Talyor graph of models

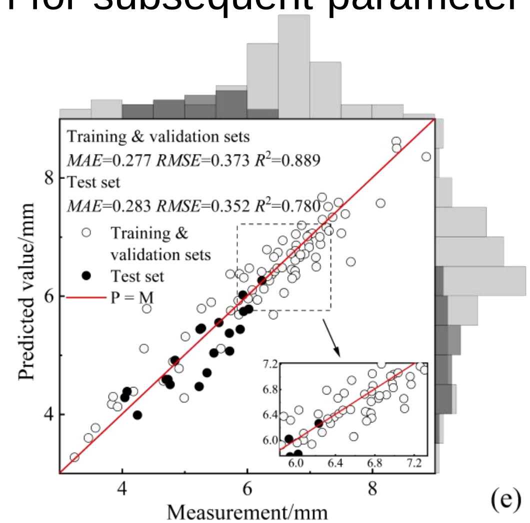


Fig. S9 Predictive performance of the entire data set: (e) The MHSA-Bi-LSTM model

Preserving Physical Constraints in Engineering

Case Study: Field Data Verification of Changchun Metro Line 6 (Rings 715-910).

Full Optimization vs. Adaptive Strategy:

- **Traditional full-parameter optimization:** The uncontrollable parameters deviated from the actual engineering constraints by an average of ±34.27%.
- **Adaptive adjustment strategy:** The fluctuations of the uncontrollable parameters were effectively limited within ±13.95%.

The adaptive strategy perfectly matched the mechanical and mechanical transmission principle of the earth pressure balance shield.

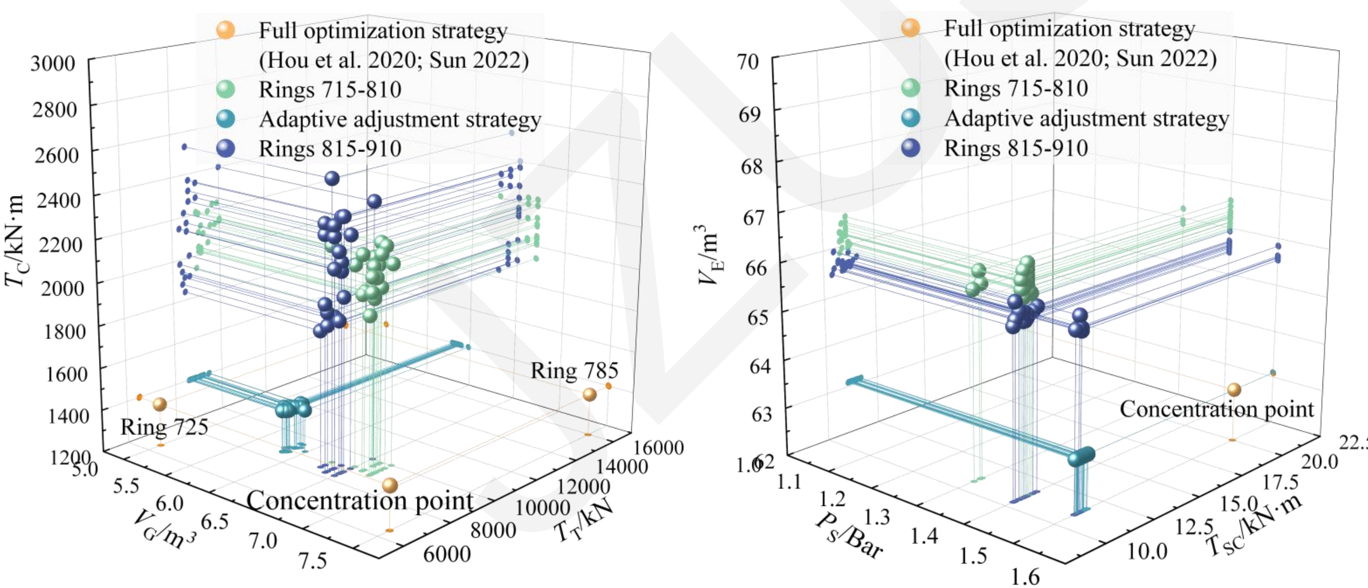


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Fig. 12 Distributions of the uncontrollable parameters of rings 715-910 in theory and practice

Significant Improvement in Settlement Pre-control

Baseline (without optimization): Average settlement 6.15 mm.

Full Optimization Strategy: Average settlement 4.72 mm (improvement of 23.25%), but due to parameter imbalance, the actual control error was relatively large.

Adaptive Adjustment Strategy (ours): Average settlement reduced to 3.81 mm (significant improvement of 38.05%).

While coordinating the parameters, a smaller and more stable pre-control of surface settlement was achieved.

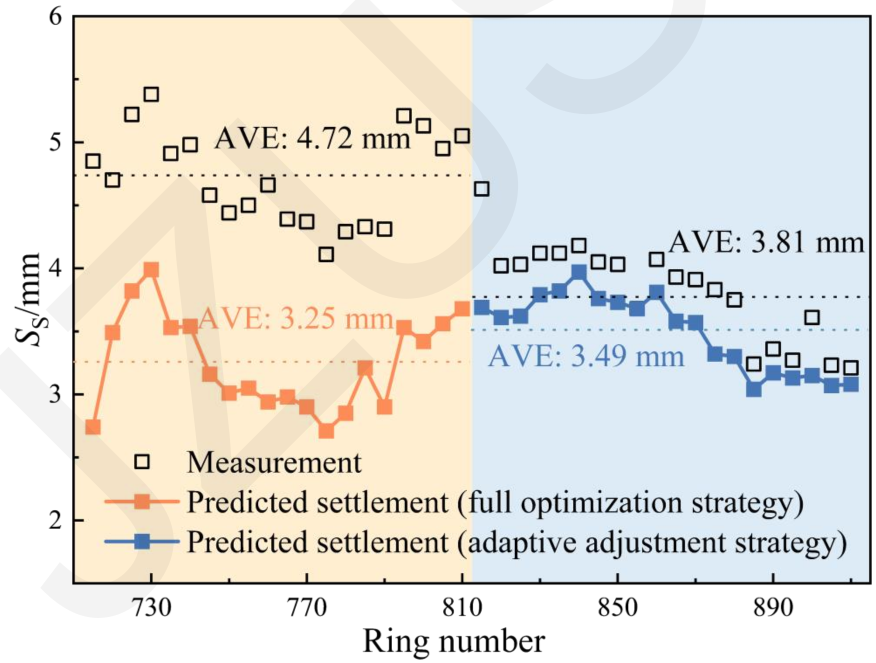

Fig. 13 S_S results for rings 715-910