A Data-Driven Deep Machine Learning Approach for Tunnel Deformation Risk Assessment

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***Abstract*—The shallow overburden pipe jacking over operation tunnel construction project in chalk stratum has the risk of deformation of the soil layer and the existing tunnel, which increases the difficulty of pipe jacking over construction, and the risk assessment and control become the key technology for the safe and successful completion of the construction. Aiming at the problems of the current deformation risk assessment and control method, such as the assessment system is not comprehensive, systematic and objective enough, the prediction accuracy is not efficient enough, and there is a lack of quantitative analysis, etc., a deformation risk assessment and control method is proposed to combine the heuristic optimization algorithm of human behaviour and deep machine learning algorithm for pipe jacking up to and across operation tunnels on shallow overburden of chalky sand stratum. Firstly, by analyzing the construction process of pipe jacking tunnel, the deformation risk factors of the construction process and the deformation risk control scheme are given; then, a deformation risk assessment and control algorithm with improved deep limit learning machine is proposed by combining human heuristic optimization algorithm; finally, the proposed deformation assessment and control model is applied to the deformation risk assessment and control problem of pipe jacking over operation tunnel on shallow overburden of pulverised sand stratum, and a finite element computational model is used to construct the data. Finally, the proposed deformation assessment and control model is applied to the problem of deformation risk assessment and control in a tunnel with shallow overburden in chalky sand stratum by using finite element computational model to construct the data set, training the deformation risk assessment and control model, and using the monitoring data as the test set to validate the validity of the proposed model algorithm, and solving the problem of the poor prediction accuracy of the control algorithm for deformation risk assessment and control of a tunnel with shallow overburden in a tunnel with shallow overburden in chalky sand stratum.**

Keywords*—*Pipe jacking up and over operational tunnel construction; tunnel deformation risk assessment; deep limit learning machine; hybrid leader optimisation algorithm; control strategy

I. INTRODUCTION

Due to the rapid development of economic technology and science and technology, the urbanisation process in China has been increasing, which has led to many problems in cities, such as traffic congestion, environmental pollution, population increase, and huge energy depletion [1]. In order to alleviate the increasingly serious pressure on urban space, the construction and development of underground space has gradually become an important way for major cities to solve the problems arising from urbanisation [2]. The construction of urban underground space includes the construction of underground tunnels, and its construction methods mainly include shield method and pipe jacking method, two urban tunnel construction methods [3]. The pipe jacking tunnel construction method, as a kind of no-excavation construction technology, achieves the construction of tunnels by setting up work shafts on the ground, and then using pipe jacking machines to push the pipeline or tunnel structure from one work shaft to another work shaft [4]. The pipe jacking tunnel construction technology has the characteristics of reducing damage to the surrounding environment, ensuring construction safety, fast construction speed, controllable quality and strong adaptability [5]. Although there are many advantages in the process of jacking tunnel construction, it is still affected by the geological environment, nearby buildings and other influences, and there is the phenomenon of frequent accidents in underground tunnel engineering, such as ground subsidence, sand and soil gushing out, and river water backing up and other problems [6]. Therefore, it is of great practical significance to study the comprehensive and systematic quantitative risk assessment and control method of tunnel deformation during the construction of pipe jacking tunnels.

Accurate and effective risk assessment methods for deformation of tunnel operating in jacked tube construction not only improve the safety of jacked tube tunnel construction, but also improve the risk management level of tunnel engineering construction [7]. Risk assessment generally includes the steps of risk mechanism analysis, risk identification, risk assessment and risk control [6]. The deformation risk assessment of roof-tube construction and operation tunnel is to analyse and identify the risk factors of roof-span jacking construction in the process of roof-tube top-span operation tunnel construction, use the risk assessment model to construct the complex law relationship between the tunnel deformation risk indexes and the value of the control strategy, and obtain the deformation control strategy of the roof-tube construction and operation tunnel based on the specific deformation situation of the tunnel [7]. Risk assessment algorithm, as one of the key technologies for deformation risk assessment of top tube over spanning operation tunnels, should not only analyse the risk of tunnel changes in the construction process from the perspective of top tube over spanning operation tunnels, but also put forward risk assessment algorithms that can describe the law according to the specificity of the problem. Currently, the research on the top tube over operational tunnels mainly focuses on the deformation of the soil layer around the top tube method and the deformation of the existing tunnel structure, and usually adopts the empirical formula method [8], the theoretical analysis method [9], and the finite element analysis method [10], etc. Literature [8] has shown that the deformation of the soil layer around the top tube method and the deformation of the tunnel structure is the main cause of the risk of tunnel changes during the construction process; Literature in [9] used random medium method and peck formula method to analyse the difference of surface settlement caused by pipe jacking construction; Literature in [10] for the problem of rectangular pipe jacking construction of large cross-section, the use of finite element software to analyse the disturbance of the soil body, and at the same time put forward the relevant construction control scheme. For the problem of risk assessment model construction, the current more popular assessment algorithms include fuzzy logic method, grey model, machine learning and other methods [11]. Due to the deformation of the top tube over operation tunnel is affected by the uncertainty and complexity of the construction risk, and at the same time, there is a nonlinear relationship between the deformation risk and the control strategy, the deformation risk assessment method of the top tube over operation tunnel based on machine learning algorithms can use the data to quickly construct an accurate model, which is paid special attention to by experts in the field, and has also become one of the directions of the development of the deformation risk intelligent analysis of the top tube construction and operation tunnel [12]. Risk assessment methods based on machine learning algorithms include BP neural networks, support vector machines, decision trees, clustering and other algorithms [13]. Although the research on deformation risk assessment algorithms for roof-tube up-and-over operation tunnels has achieved certain qualitative theoretical results, there are still some problems [14]: 1) the identification of deformation risk of roof-tube up-and-over operation tunnels is not comprehensive and systematic enough; 2) the quantitative research on the deformation control strategy of roof-tube up-and-over operation tunnels is relatively small; and 3) the precision of the deformation risk assessment model needs to be improved.

For groundwater-rich chalk strata, pipe jacking is prone to the risk of over-excavation due to gushing, which affects the stability of the surrounding strata. Compared with general clay and weathered rock strata, there are fewer construction practices in the engineering community for pipe jacking across highly sensitive soils such as chalk strata, and there is a lack of deformation control measures for existing structures that are compatible with such strata [15]. In order to analyse the deformation risk mechanism of pipe jacking across operational tunnels in shallow overburden in chalky sand strata and to quantify the precise deformation risk control measures, machine learning algorithms are used to construct a deformation risk assessment and control model for pipe jacking across operational tunnels in shallow overburden in chalky sand strata.

In order to solve the problems of deformation risk assessment and control method of pipe jacking over operation tunnel, this paper proposes a risk assessment and control method based on hybrid leader optimisation algorithm to improve the depth limit learning machine. In view of the deformation risk problem of shallow overburden pipe jacking over operation tunnel in chalk stratum, the deformation risk mechanism is analysed, and the deformation risk factors and control indexes in the construction process are introduced; in view of the deformation risk assessment and control problem of the tunnel, the hybrid leader optimization algorithm is used to optimize the network of the deep limit learning machine, and the proposed general application is applied to the specific problems. The effectiveness and robustness of the proposed algorithm is verified by analysing the structural numerical simulation data with the case of a close-range up-span underground operation tunnel in chalky sand formation.

The paper's framework begins with an analysis of the deformation mechanisms involved in pipe-jacking tunnel construction within chalky sand strata, focusing on key factors that influence deformation risk and stability control. Following this, it introduces a hybrid machine learning model that combines a Deep Limit Learning Machine (DELM) with a Hybrid Leader-Based Optimization (HLBO) algorithm to enhance prediction accuracy and model robustness. This model is then applied to a case study in Hangzhou, China, where pipe-jacking occurs near existing metro tunnels, with simulations and field measurements used to test accuracy. Comparative experiments validate the model's effectiveness against other methods, presenting detailed parameter evaluations and monitoring data. The paper concludes by discussing the model's contributions to improving deformation risk assessment in tunnel engineering, noting its limitations and proposing areas for further research to increase predictive accuracy and computational efficiency.

II. Analysis of Deformation Risks and Control Options for Pipe Jacking

A. Pipe Jacking Tunnel Construction Process

Pipe jacking tunnelling is a trenchless construction technique, which is mainly used for the construction of urban underground pipelines, subways, pedestrian passages and other projects. This technology achieves tunnel construction by setting up work shafts on the ground and then using pipe jacking machines to push the pipeline or tunnel structure from one work shaft to another, as shown in Fig. 1. Pipe jacking construction technology has the characteristics of reducing damage to the surrounding environment, ensuring construction safety, fast construction speed, controllable quality and strong adaptability.

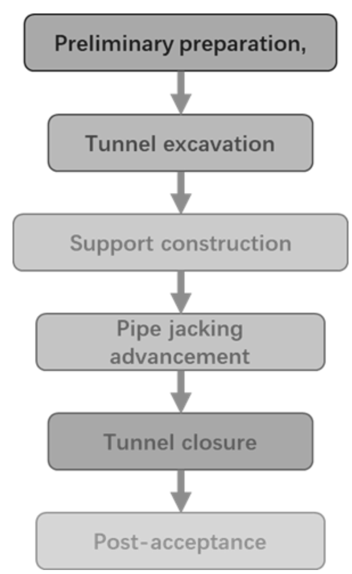

Fig. 1. Construction process of pipe jacking tunnelling.

As shown in Fig. 1, it can be seen that the process of pipe jacking tunnel construction includes pre-preparation, tunnel excavation, support construction, pipe jacking advancement, tunnel closure, and post-acceptance [16].

1) Pre-preparation: Determine the tunnel construction area, carry out geological survey and design, and formulate detailed construction plan, including propulsion path and propulsion machinery selection.

2) Tunnel excavation: traditional tunnel excavation methods, such as blasting or roadheader method, are used to open up a large enough tunnel space for pipe jacking construction.

3) Support construction: choose the appropriate support method according to the geological condition, such as steel frame support, spray anchor support, etc., to ensure the stability and safety of the tunnel.

4) Pipe jacking advancement: choose suitable pipe jacking machinery to carry out the advancement operation, and support the tunnel wall during the advancement process to prevent collapse and instability.

5) Tunnel closure: When the jacking pipe advances to the target position, the pipe closure and connection work is carried out to ensure the sealing and use function of the tunnel.

6) Post-acceptance: acceptance of construction quality, check whether pipe jacking construction meets the requirements to ensure the quality of the project.

B. Project Orientated Risk Analysis of Deformation during the Construction Process

1) Introduction to the project: In order to verify the effectiveness of the deformation risk assessment and control method of the pipe jacking across the operation tunnel, this paper adopts the pipe jacking construction project of Xinfeng Road underground passage in Linping District of Hangzhou City as an analysis sample.

Xinfeng Road Underpass in Linping District, Hangzhou is located in the north side of the intersection of Xinfeng Road and Wenzheng Street in Linping District, and there are many existing structures within the new construction scope. The underpass passes through Xinfeng Road, a main road (header pipe depth 2.3m), and crosses (minimum vertical clearance between header pipe and tunnel structure 2.5m) the existing Hangzhou Metro Line 9 Yuhang High Speed Railway Station to Nanyuan Station double line tunnel, and passes through the existing Hanghai Intercity Double Line Tunnel in parallel (horizontal clearance between header pipe and tunnel 15.6m). The relative position of the underpass and the existing structure is shown in Fig. 2.

The pipe jacking section of the underpass passes through the shield tunnel of Metro Line 9 (inner diameter 5.5m, wall thickness 350mm) and the shield tunnel of Hanghai Intercity (inner diameter 6.0m, wall thickness 350mm).

According to the results of ground investigation, the pipe jacking section is mainly located in ②2 sandy silt and ④ silt stratum, the upper layer is ① miscellaneous fill and ②1 clayey silt stratum, and the layer where the tunnel is located in the lower zone is ④ silt and ⑥ clay stratum, and the physico-mechanical parameter of the soil stratum is shown in Table I.

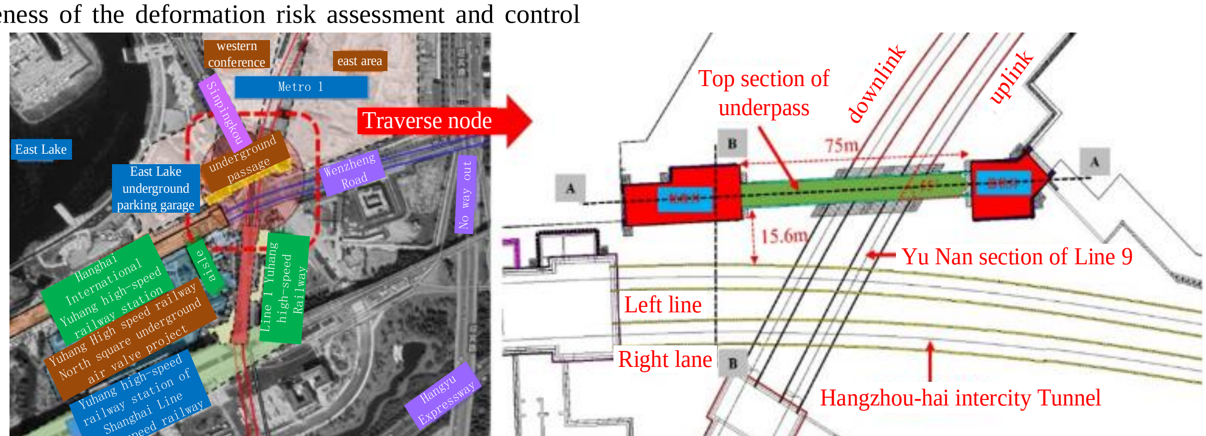

Fig. 2. Relationship between the plan position of the underground passage and the existing structure.

TABLE I. PHYSICAL-MECHANICAL PARAMETERS OF LANDMARKS

Layer number	Stratum	Water content/%	Pore ratio/%	Natural gravity/(kN/m^3)	Cohesion/kPa	Angle of internal friction/°	Horizontal permeability coefficient k/(×10^{-4}cm/s)	Vertical permeability coefficient k /(×10^{-4}cm/s)
①	mixed soil	(30.0)		(19.0)	(7.0)	(15.0)		
②$_1$	clayey silt	25.5	0.731	19.09	5.6	17.6	0.63	0.49
②$_2$	sandy silt	24.6	0.693	19.25	3.0	21.6	7.4	6.1
④	siltstone	24.2	0.677	19.28	3.3	23.4	53.4	37.8
⑥	clays	27.6	0.811	18.88	34.4	14.4		

2) Deformation analysis of pipe jacking construction process: The pipe jacking method of construction generally causes deformation of the ground and the existing tunnel [17].

The deformation of the ground includes ground loss and reconsolidation of disturbed soil. The deformation of stratum mainly refers to the difference between the actual soil volume and the completed tunnel volume during the pipe jacking construction process, and the factors that cause the loss of stratum include soil excavation, pipe section size, tool pipe dragged with soil, pipe jacking correction, pipe section rebound and so on. Re-consolidation of disturbed soil refers to the re-consolidation of disturbed soil after the end of pipe jacking construction, resulting in deformation of the soil layer again, and the main factors include the decrease of void pressure and the disappearance of super pore water pressure.

The deformation of an existing tunnel includes both lateral and vertical deformation [18].

In order to construct an accurate tunnel deformation risk assessment and control model, the tunnel deformation risk factor set is firstly established from two perspectives: ground deformation and existing tunnel deformation, as shown in Fig. 3.

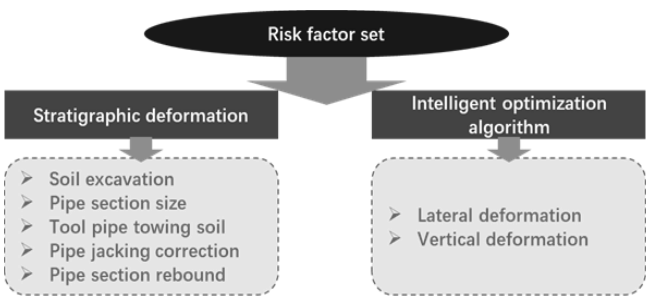

Fig. 3. Tunnel deformation risk factor set.

3) Specific analysis of deformation risk: In this project, there was excessive deformation of the existing tunnel during the jacking construction of the pipe jacking section, mainly focusing on two aspects.

a) Aspects of deformation in chalk strata: Firstly, the project is located in the stratum of silt sand stratum, with high compressibility, high sensitivity and thixotropy, and unfavourable deformation control after stratum construction; secondly, the project is adjacent to the East Lake, with large water content in the stratum, and easy to occurrence of groundwater gushing in the process of jacking.

b) Deformation of existing tunnels: The jacking pipe penetrates the operation tunnel with a vertical clearance of 2.5m, which causes the ground stress relaxation in the unloading disturbance area and the shear disturbance area, and the structure of the operation tunnel near the bottom rises upwards with the surrounding strata; the soil overlay above the jacking pipe is relatively shallow, and the jacking construction has a large impact on the ground surface deformation, as shown in Fig. 4.

C. Deformation Risk Control Programme

In order to analyse the impact of the construction process of the pipe jacking project on the deformation of the operation tunnel, in order to minimise the project risk, the existing tunnel inspection situation is taken into account to determine the structural and surface deformation control scheme of the existing tunnel in the area during the construction process of the pipe jacking project. The existing tunnel structure and surface deformation control program during the construction process of the pipe jacking project is mainly expressed in the form of safety control indicators.

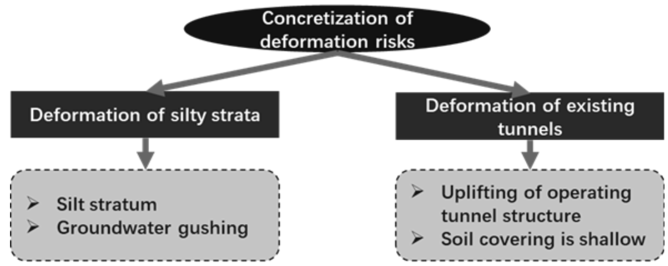

Fig. 4. Schematic diagram for specific analysis of tunnel deformation risk.

The deformation control index of the interval during the construction process of the pipe jacking upper span project is designed from the deformation control of the existing tunnel structure and the surface deformation control in two aspects of the index value [19], in which the deformation control of the existing tunnel structure includes the safety control index and the deformation rate control index [20], as shown in Table. II

TABLE II. SCHEMATIC DIAGRAM OF DEFORMATION CONTROL INDICATORS

ltems	Indicators
Existing tunnels	Horizontal displacement of the tunnel
	Vertical displacement of the tunnel
	Tunnel differential settlement
	Tunnel radial convergence
	Rail transverse height difference
	Shield segment joint opening
	Settlement of tunnel structures
	Tunnel structure floats upward
	Horizontal displacement of structure
Surface	Surface uplifting
	Surface subsidence

In view of the shallow soil cover above the jacking tube, 300mm thick reinforced concrete slabs are used for road hardening on the surface above the jacking section of the channel to reinforce the strength of the ground surface, reduce the surface uplift in the jacking process, slow down the effect of shallow soil cover on the deformation of the operation tunnel and act as counterweights above the jacking tube.

III. IMPROVED DEEP LIMIT LEARNING MACHINE MODEL

Deep Extreme Learning Machine is a deep neural network stacked by multiple Extreme Learning Machine self-encoders with fast training speed and good generalisation performance [21]. In order to overcome the problem that the random input weights and biases of deep extreme learning machine affect the training effect, this paper proposes a deep extreme learning machine model based on hybrid leader optimisation algorithm.

A. Deep Limit Learning Machine

The limit learning machine [22] is denoted as

$$f_{ELM}\left(x_i\right)=\sum_{j=1}^{l}\beta_j g\left(a_j x_i+b_j\right), i=1,2,\cdots,N \quad (1)$$

Where $\beta_j=\left[\beta_{j1},\beta_{j2},\cdots,\beta_{jn}\right]$ denotes the output weights, $a_j=\left[a_{j1},a_{j2},\cdots,a_{jm}\right]$ denotes the input weights, b_j denotes the bias, and $g\left(\cdot\right)$ denotes the activation function.

The ELM output error is

$$\begin{aligned} E&=\sum_{i=1}^{N}\left\| f_{ELM}\left(x_i\right)-y_i\right\| \\ &=\left\|\boldsymbol{H}\left(\boldsymbol{a},\boldsymbol{b}\right)\cdot\beta-\boldsymbol{y}\right\| \end{aligned} \quad (2)$$

Where, $\boldsymbol{H}$ denotes the output, β denotes the output weights and $\boldsymbol{y}$ denotes the desired output. In ELM algorithm, by determining $\boldsymbol{a}$ and $\boldsymbol{b}$, $\boldsymbol{H}$ is uniquely determined. The output weights are solved by the formula

$$\boldsymbol{\beta}^*=\boldsymbol{H}^{-1}\cdot\boldsymbol{y} \quad (3)$$

where $\boldsymbol{H}^{-1}$ denotes the Moore-Penrose generalised inverse matrix of the matrix $\boldsymbol{H}$.

Deep extreme learning machine (DELM) output weights are

$$\boldsymbol{\beta}^*=\boldsymbol{H}^{-1}\left(\frac{1}{C}+\boldsymbol{H}\boldsymbol{H}^T\right)^{-1}\cdot\boldsymbol{y} \quad (4)$$

Where, C tables the regular term coefficients.

B. Hybrid Leader Optimisation Algorithm

In intelligent optimisation algorithms, the individuals of the population act as searchers in the problem space, which are candidates for solving the problem, and update the position information through continuous iterative optimisation and comparison to provide a better solution. In this paper, we propose a leader-inspired intelligent optimisation algorithm, Hybrid leader based optimization (HLBO), which uses the best member, a random member, and the corresponding member to update and guide the position information of the population [23].

Like other heuristic algorithms, the population representation of the HLBO algorithm is as follows:

$$X=\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_N \end{bmatrix}_{N\times m}=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ x_{N1} & x_{N2} & \cdots & x_{Nm} \end{bmatrix}_{N\times m} \quad (5)$$

At the beginning of the optimisation process, the population, N individuals are randomly initialised with the following initialisation formula:

$$x_{ij}=lb_j+rand\times\left(ub_j-lb_j\right), j=1,2,\cdots,m \quad (6)$$

In HLBO, two search phases are proposed based on leader behaviour: an exploration (global) phase and an exploitation (local) phase.

1) Exploration (global) phase: The exploration phase usually allows the population individuals to precisely search different spaces to reach the original optimal region. Continuous dependence on population-specified individuals can prevent global search and reduce the exploration operation of the algorithm, which results in the population individuals falling into a local optimum. In the HLBO algorithm, a hybrid leadership strategy is used to update the population, and its strategy mainly depends on the current individual, optimal individual, and random individual position information.

The participation factors of current individual, optimal individual, and random individual make the calculation based on individual quality, and the specific formula of individual quality is as follows:

$$q_i=\frac{F_i-F_{worst}}{\sum_{j=1}^{N}\left(F_i-F_{worst}\right)}, i\in\left\{1,2,\cdots,N\right\} \quad (7)$$

The participation factor for each member is calculated as follows:

$$PC_i=\frac{q_i}{q_i+q_{best}+q_k} \quad (8)$$

$$PC_{best}=\frac{q_{best}}{q_i+q_{best}+q_k} \quad (9)$$

$$PC_k=\frac{q_k}{q_i+q_{best}+q_k} \quad (10)$$

Where q_i denotes the individual quality, F_i denotes the fitness value, F_{worst} denotes the fitness value of the worst solution, and PC_i , PC_{best} and PC_k denote the participation factors of the *ith* candidate solution, the optimal solution, and the *kth* candidate solution, respectively.

Based on the calculation of the participation factor, the hybrid leader location information is:

$$HL_i=PC_i\cdot X_i+PC_{best}\cdot X_{best}+PC_k\cdot X_k \quad (11)$$

where HL_i denotes the hybrid leader generated by the *ith* candidate solution and X_k denotes a randomly selected individual. The *ith* individual position update is based on the guidance of the hybrid leader.

$$x_{ij}^{new,p1} = \begin{cases} x_{ij} + r \cdot \left(HL_{ij} + I \cdot x_{ij} \right) & F_{HL_i} < F_i \\ x_{ij} + r \cdot \left(x_{ij} - HL_{ij} \right) & otherwise \end{cases} \quad (12)$$

The HLBO algorithm uses an elite strategy to select individuals as follows:

$$X_i = \begin{cases} X_i^{new,p1} & F_i^{new,p1} < F_i \\ X_i & otherwise \end{cases} \quad (13)$$

Where, $X_i^{new,p1}$ denotes the new position of the *ith* candidate solution, $F_i^{new,p1}$ is the fitness value of $X_i^{new,p1}$, r denotes the random number between $[0,1]$, I is a randomly selected integer from the integer set $\{1,2\}$, and F_{HL_i} denotes the mixed leader fitness value of the *ith* candidate solution.

2) Development (partial) phase: The development phase is a localised search to obtain better solutions in the vicinity of the solution. In the HLBO algorithm, each individual neighbourhood region can allow an individual search to find a better candidate solution. In the development phase, the local search strategy is modelled as follows:

$$x_{ij}^{new,p2} = x_{ij} + (1-2r) \cdot R \cdot \left(1 - \frac{t}{T}\right) \cdot x_{ij} \quad (14)$$

$$X_i = \begin{cases} X_i^{new,p2} & F_i^{new,p2} < F_i \\ X_i & otherwise \end{cases} \quad (15)$$

Where, $X_i^{new,p2}$ denotes the new position of the local phase of the *ith* candidate solution, $F_i^{new,p2}$ is the fitness value of $X_i^{new,p2}$, R is a constant set to 2, t denotes the current number of iterations, and T is the maximum number of iterations.

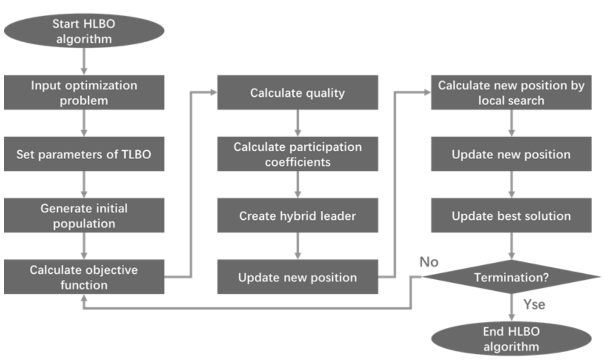

Fig. 5. Flowchart of HLBO algorithm.

3) Process steps: Based on the analysis and description of the above strategies and mechanisms, the flow of the KOA algorithm is shown in Fig. 5.

C. DELM Model based on HLBO Algorithm

1)Coding method: In this paper, the real number coding method is used to encode the hidden layer parameters, which is shown in Fig. 6.

Fig. 6. Encoded DELM parameters.

2) Adaptation function: In this paper, RMSE [24] is used as the adaptation function:

$$RMSE = \sqrt{\left(\sum_{i=1}^{M} \left(\hat{y}_i - y_i \right)^2 \right) \Big/ M} \quad (16)$$

3) HLBO-DELM methodology: According to the encoding method and fitness function, the flowchart of the deep limit learning machine model step method based on the HLBO algorithm is shown in Fig. 7.

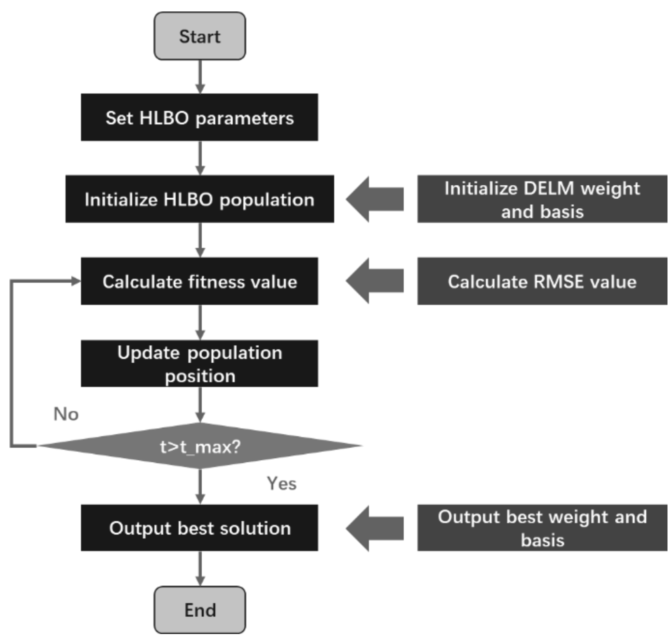

Fig. 7. HLBO-DELM methodology.

D. Application of the HLBO-DELM Model

In order to construct a deformation risk control model for shallow overburden pipe jacking operation tunnels in chalky sand strata, this paper adopts the HLBO-DELM model, by analysing the tunnel deformation risk factors and control indexes, taking the weights and biases of the DELM as the optimisation variables, and taking the RMSE values between the analytical tunnel deformation risk control indexes and the predicted values and the simulated values as the fitness value function, the optimisation strategy of the HLBO algorithm is used to find out the optimal weights and biases of the DELM. The HLBO-DELM model application principle and framework structure are shown in Fig. 8.

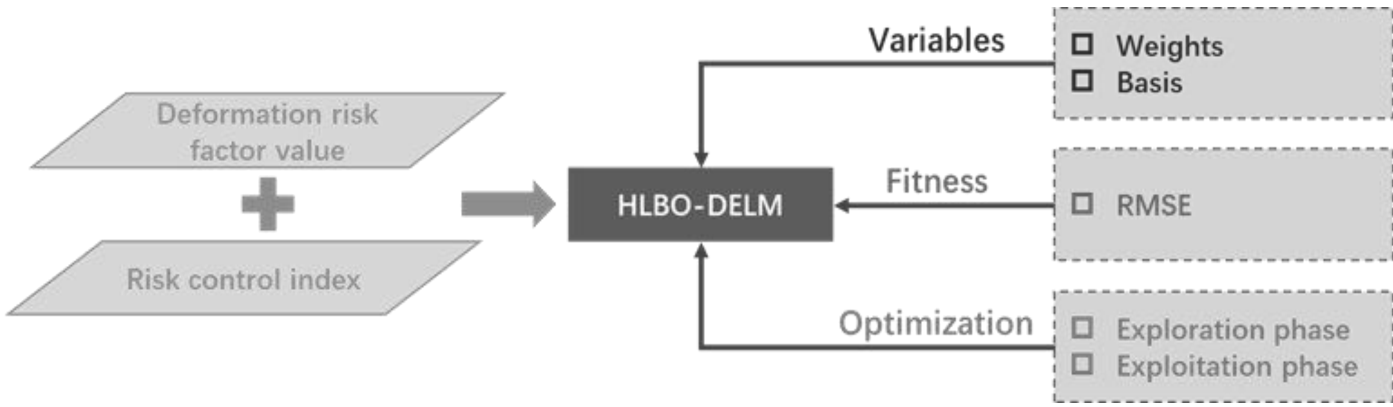

Fig. 8. HLBO-DELM application analysis.

IV. Tunnel Deformation Risk Assessment and Control Process Methodology

Combined with the HLBO-DELM model oriented to the tunnel deformation risk assessment and control problem, this subsection analyses the mapping relationships that need to be constructed in the HLBO-DELM model and gives the tunnel deformation risk assessment and control method flow.

A. Analysis of Model Mapping Relationships

The deformation risk assessment factors of the operation tunnel over shallow cope pipe in chalk stratum are set up from the perspective of ground deformation and existing tunnel deformation, and the deformation control indexes of the operation tunnel over shallow cope pipe in chalk stratum are mainly designed from the control of structural deformation of the existing tunnel and the control of ground surface deformation. The specific construction results are shown in Fig. 9.

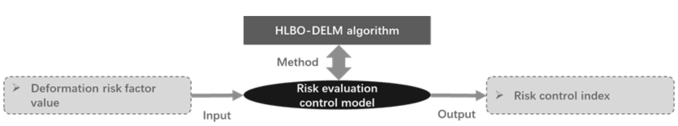

Fig. 9. Schematic diagram of model mapping relationship analysis.

B. Methodological Process

In order to improve the deformation risk assessment and control of the roof-tube up-and-over operation tunnel, this paper investigates the tunnel deformation risk assessment and control method using a combination of intelligent optimisation algorithm and machine learning algorithm, and the specific process is shown in Fig. 10.

As can be seen from Fig. 10, in the construction risk assessment and control scheme of the top tube over operation tunnel, through analysing the deformation risk factors and risk control index set of the top tube over operation tunnel, pre-processing the raw data, combining with HLBO-DELM, constructing the deformation risk assessment and control model of the top tube over operation tunnel, predicting and analysing the amount of deformation control, and improving the precision and accuracy of risk control.

Step 1: Identify and analyse the deformation risk factors of the top tube over the operational tunnel by using expert consultation, experimental demonstration and work breakdown structure method;

Step 2: Analyse and design a set of deformation risk control indicators for the top tube over operational tunnels in terms of both deformation of existing tunnels and deformation of the ground;

Step 3: Construct a sample set of labelled deformation risk factor-risk control indicators;

Step 3: Normalise the original data samples using techniques such as outlier removal, missing value supplementation, normalisation, etc., and perform feature extraction and dimensionality reduction of the input vectors using the Kernel Principal Component Analysis (KPCA) [25] method;

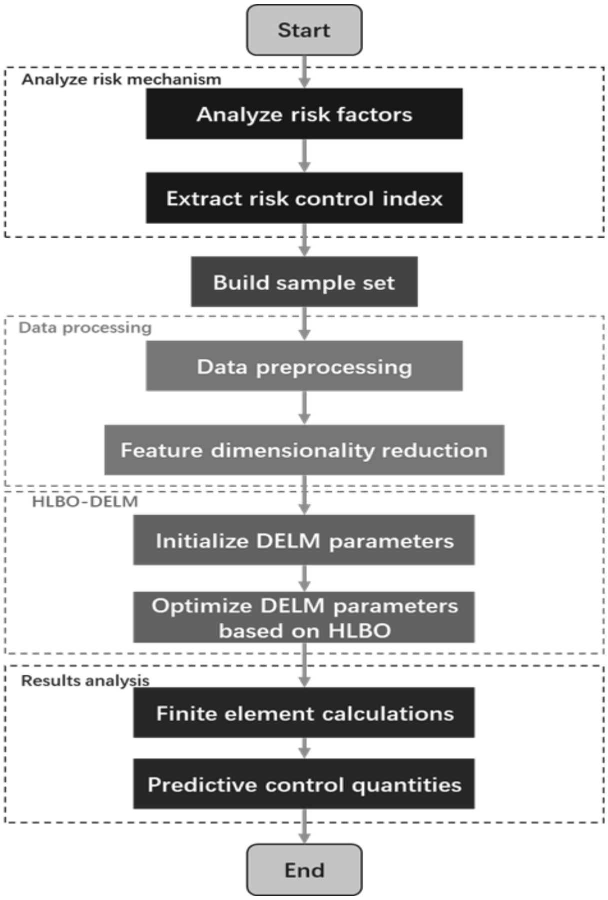

Fig. 10. Flow of tunnel deformation risk assessment and control method.

Step 4: Combine the HLBO-DELM algorithm to construct a deformation risk assessment and control model for the top tube over operation tunnel;

Step 5: Numerical Analysis of Risk Control Measures Experimental Finite Element Computational Models [26] A certain number of samples are constructed and divided into training set, validation set, and testing set;

Step 6: Train the model, analyse the results of the test set, and at the same time collect the project engineering risk factors and input them into the assessment and control model to obtain the deformation risk control index value of the top tube over the operational tunnel.

V. Analysis of Numerical Experiments

A. Experimental Setup

In order to verify the effectiveness and feasibility of the deformation risk assessment and control algorithm of the pipe jacking over operation tunnel proposed in this paper, this paper takes the project of close crossing over Metro Line 9 tunnel and side crossing over Hanghai Intercity Tunnel of Xinfeng Road Underpass in Hangzhou as an analysis sample, and selects DELM, PSO-DELM, GWO-DELM, HHO-DELM, WOA-DELM and HLBO-DELM to compare with the algorithms. algorithms for comparison.

1) Algorithm parameter setting: In Table III, DELM uses Moore-Penrose generalised inverse matrix to solve the optimal structural parameters, PSO-DELM, GWO-DELM, HHO-DELM, WOA-DELM and HLBO-DELM use intelligent optimisation algorithm to solve the optimal structural parameters, the maximum number of iterations of intelligent optimisation algorithm is 100, the number of population counts is 50, and the number of hidden layers is 2.

TABLE III. Comparison Algorithm Parameter Settings

Arithmetic	Parameterisation
DELM	Two hidden layers with 30, 30 nodes in each layer
PSO-DELM	Vmax=30, Vmin=-30, r=0.5
GWO-DELM	GWO algorithm a control parameters using a linear decreasing strategy
HHO-DELM	E0 in the range (-1, 1)
WOA-DELM	The WOA algorithm a decreases from 2 to 0, and the spiral shape parameter is 1.
HLBO-DELM	r denotes a random number between 0 and 1 and I denotes a randomly chosen integer of {1,2}

2) Environmental settings: The experimental simulation environment is Win 10, the risk assessment algorithm programming language Python 3.8, and the structural numerical analyses are performed using Midas GTS finite element software.

B. Analysis of Results

1) Numerical analysis of structures: Using the software for pipe jacking construction simulation, the calculation results after the jacking advancement in the characteristic working condition are shown in Table IV. As can be seen from Table IV, the largest vertical deformation in the deformation of the tunnel structure of Line 9 is the bulge of 4.86mm when completing the construction of the upper span, which occurs in the tunnel tube sheet of the downstream line of Line 9, as shown in Fig. 15. Since the final bulge deformation in this case is due to ground loss and subsequent deformation of the ground, the tunnel bulge deformation will be smaller than the final deformation of 4.86mm when the roof tube is jacked through the tunnel directly above the Line 9 tunnel. The maximum horizontal deformation of the metro tunnel is 0.70mm, while the deformation of the Hanghai Intercity Tunnel is very small compared with that of the metro tunnel, with the maximum horizontal deformation and vertical uplift of 0.49mm and 0.83mm, respectively. according to the results of the calculation, the deformation of the two operating tunnels meets the control requirement of 5mm. The difference settlement at the junction between the tunnel section and the station is small.

2) Parametric analysis: The specific results of the analysis of the number of network hidden layer nodes parameter are shown in Fig. 11 and Fig. 12. From Fig. 11, it can be seen that the number of network hidden layer nodes increases, the accuracy of deformation risk assessment and control increases, and when the number of network hidden layer nodes increases to 100, the deformation risk assessment and control algorithm RMSE is minimum. From Fig. 12, it can be seen that the number of network hidden layer nodes of DELM increases, and the control time of each algorithm increases; the assessment and control prediction time of the HLBO-DELM model is smaller than that of other models. In summary, the number of hidden layer nodes of DBN network selected in this paper is 100.

3) Example analysis: This subsection compares the performance of the DELM, PSO-DELM, GWO-DELM, HHO-DELM, WOA-DELM and HLBO-DELM methods using the numerical simulation test set.

Firstly, continuous automated monitoring of the Metro Line 9 tunnel was carried out during the implementation of the jacking crossing site and subsequent deformation stabilisation, and the structural deformation of the tunnel after completion of the jacking upper span construction is shown in Fig. 18.

TABLE IV. STRUCTURAL DEFORMATION RESULTS OF OPERATIONAL TUNNELS DURING THE CONSTRUCTION PROCESS

working condition	Line 9 tunnel/mm		Hanghai Intercity Tunnel/mm		Differential settlement at junction/mm	
	horizontal	vertical	horizontal	vertical	Line 9 Interval	Hang Hai District
Shaft Phase 1	0.34	0.22	0.32	0.14	-	-
pipe jacking	0.36	4.86	0.49	0.83	-	-
Shaft Phase 2	0.70	4.64	0.40	0.51	0.02	0.02

Fig. 13 and Fig. 14 give the monitoring results of the roadbed displacement in the tunnel. From Fig. 13 and Fig. 14, it can be seen that the maximum value of vertical displacement in the metro tunnel is 4.0mm, which occurs in the bed measurement point of the downstream line, and the displacement of the downstream line traversed by the jacking tube first is generally larger than that of the upstream line; the maximum value of horizontal displacement is 2.7mm, which occurs in the bed measurement point of the upstream line. The maximum horizontal displacement was 2.7mm, which appeared at the upstream line bed measurement point. The larger values of vertical and horizontal displacements in the upstream and downstream lines were distributed in the area where the jacking pipe traversed, which indicated that the jacking pipe's close spanning construction had a greater impact on the operation tunnel, and the area within 25m directly below the crossing belonged to the strong impact area; the distance from this boundary to 50m had a weaker impact and belonged to the weak impact area; and the area outside of 50m belonged to the non-influence area.

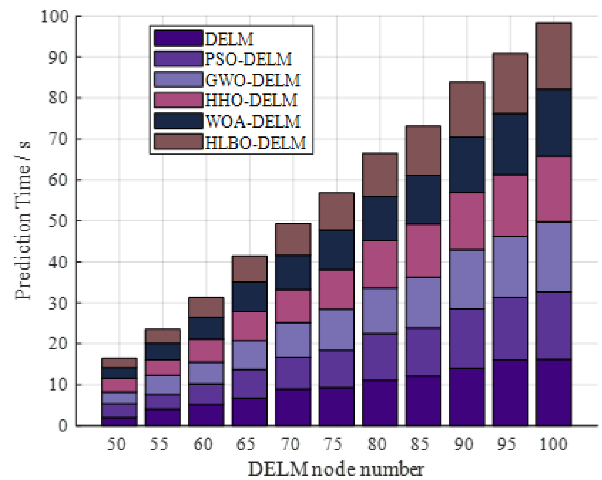

Fig. 12. Effect of different number of hidden layer nodes on control algorithm time for deformation risk assessment.

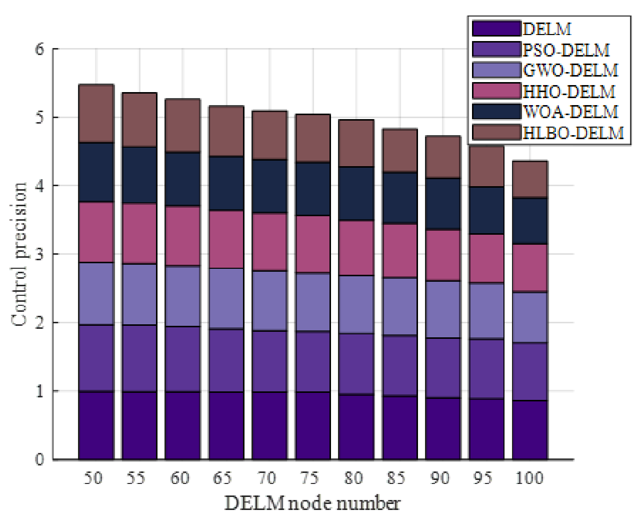

Fig. 11. Effect of different number of hidden layer nodes on the accuracy of control algorithm for deformation risk assessment.

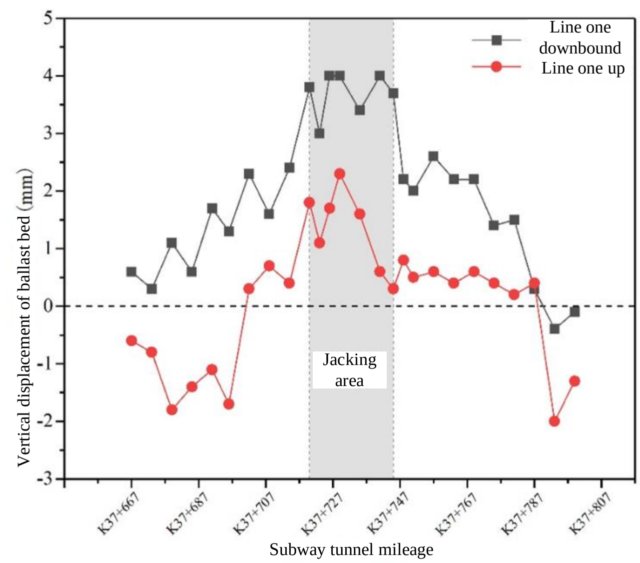

Fig. 13. Vertical displacement of tunnel bed of Line 9 metro tunnel.

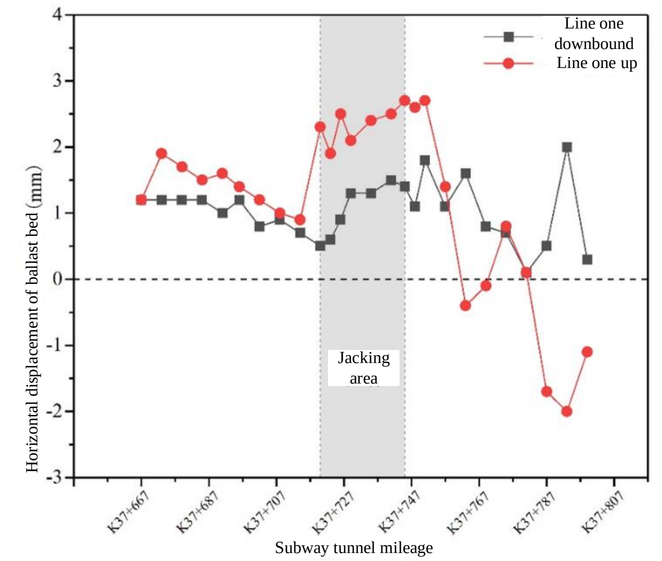

Fig. 14. Horizontal displacement of tunnel bed of Line 9 metro tunnel.

VI. Conclusion and Outlook

As the key technology of deformation risk assessment-control in the construction of roof-tube span, the deformation risk assessment-control algorithm not only reduces the subjectivity and empirical nature of the human-designed control scheme, but also constructs a complex mapping relationship between the risk identification factors and the risk control strategy. In this paper, a deformation risk assessment and control scheme is designed by analyzing the construction process of pipe jacking tunnels and the deformation risk mechanism. Meanwhile, a deformation risk assessment and control algorithm based on TLBO-DELM is proposed for the mapping relationship of the deformation risk assessment and control model, which is applied to the deformation risk and control scheme of pipe jacking up and over operation tunnels with shallow overburden in chalky sand layer, and the effectiveness of the proposed TLBO-DELM model algorithm is analyzed, and the effectiveness of the proposed TLBO-DELM model algorithm is compared with that of the other models. The effectiveness of the proposed TLBO-DELM model algorithm is analysed, and by comparing other model algorithms, it is verified that the deformation risk assessment and control model based on the TLBO-DELM algorithm has a high control prediction accuracy.

While the HLBO-DELM model has shown promise, several limitations remain. Firstly, its generalizability across different geological conditions, such as expansive soils or hard rock layers, requires further validation; performance may vary significantly in these settings. Additionally, the current study relies primarily on simulated data for model training, with limited use of real-world engineering data, which may reduce the model's robustness when applied to diverse tunnel construction projects. The algorithm's computational efficiency and real-time application also pose challenges, particularly in high-dimensional data processing and timely monitoring feedback.

To address these issues, future research should prioritize expanding the dataset by incorporating monitoring data from diverse geological contexts and construction projects, improving the model's adaptability and prediction accuracy. Enhancements in the algorithm's structure—potentially through hybridization with other optimization methods like genetic algorithms or particle swarm optimization—could strengthen its global search capability and computational speed. Moreover, integrating the HLBO-DELM model within a real-time monitoring and alert system would allow for proactive risk detection and control, facilitating automated responses to potential deformation risks in active construction sites.

References

[1] Liu Y , Song H L , Sun X D , Xing H P, Feng C Y, Zhao G. T. Characteristics of rail deformation caused by tunnel floor heave and corresponding running risk of high-speed train[J].Construction and Building Materials, 2022.

[2] Yu C .Risk Assessment of Tunnel Face Instability under Multi Factor Coupling Based on Conditional Probability and Tunnel Construction Mechanics[J]. .Applied Sciences, 2022, 12.

[3] Zheng X , Wu K , Shao Z , Yuan B, Zhao N. Tunnel Squeezing Deformation Control and the Use of Yielding Elements in Shotcrete Linings: a Review[J]. Materials (Basel, Switzerland), 2022, 15(1).

[4] Manouchehrian A , Kulatilake P .Numerical study on rock failure around a tunnel destressed by a conceptualized notched technique[J].Underground Space, 2022.

[5] Ding Z , Zhang M B , Zhang X , Wei X J. Theoretical analysis on the deformation of existing tunnel caused by under-crossing of large-diameter slurry shield considering construction factors[J].Tunnelling and Underground Space Technology, 2023, 133:104913-.

[6] Ansari A , Rao K S , Jain A K .Application of Microzonation Towards System-Wide Seismic Risk Assessment of Railway Network[J].Transportation Infrastructure Geotechnology, 2024, 11(3):1119-1142.

[7] Han X , Oreste P , Ye F .The important role of stiffnesses values of circular joints on the stress state developed in the tunnel segmental lining[J]. Geomechanics and Geophysics for Geo-Energy and Geo-Resources, 2023, 9(1).

[8] LI Zhongchao, CHEN Renpeng, MENG Fanyan, YE Junneng. Relationship between ground deformation and boring parameters for shield tunneling in soft clay[J]. Journal of Zhejiang University (Engineering Edition), 2015, 49(7): 1268-1275.

[9] Shi Chenghua, Huang Linchong. Calculation of soil deformation in disturbed area of tunnel for pipe jacking construction[J]. Journal of Central South University (Natural Science Edition),2005,(02):323-328.

[10] Jin Xin. Soil Disturbance Law and Control Technology of Large Section Rectangular Pipe Jacking Under the Beijing-Hangzhou Grand Canal [D]. China University of Mining and Technology,2020.

[11] Zhang B , Tao Z , Guo P . Model test on deformation and failure mechanism of tunnel support with layered rock mass under high ground stress[J].Engineering failure analysis,. 2023.

[12] Wu P , Lin F , Huang J , Xu Y. Multiscale evaluation of tunnel construction safety risk: a case study of an offshore tunnel construction in Ningbo[J]. Journal of Engineering and Applied Science, 2024, 71(1).

[13] Rautioaho E , Korkiala-Tanttu L .Bentomap: Survey of bentonite and tunnel backfill knowledge - State-of-the-art[J].Tanttu, 2022.

[14] Shi J , Chen Y , Kong G ,Lu H, Chen G, Shi C. Deformation mechanisms of an existing pipeline due to progressively passive instability of tunnel face. Physical and numerical investigations[J].Tunnelling and Underground Space Technology incorporating Trenchless Technology Research, 2024, 150.

[15] Fogang P M , Liu Y , Zhao J , Ka T A, Xu S. Analytical Prediction of Tunnel Deformation Beneath an Inclined Plane: Complex Potential Analysis[J].Applied Sciences, 2023.

[16] Qi X .Three-dimensional inversion of controlled-source electromagnetic data for surveying the Jiutianshan high-speed railway Tunnel, China [J] .Journal of Applied Geophysics, 2023, 209:104901-.

[17] Su D , Chen W , Wang X , Huang M, Pang X, Chen X. Numerical study on transverse deformation characteristics of shield tunnel subject to local soil loosening[J].Underground Space, 2022, 7(1):106-121.

[18] Yasuda N , Cui Y .Deformation estimation of a circular tunnel from a point cloud using elliptic Fourier analysis[J].Tunnelling and underground space technology, 2022(7):125.

[19] Xu X , Wu Z , Liu Q .An improved numerical manifold method for investigating the mechanism of tunnel supports to prevent large squeezing deformation hazards in deep tunnels[J].Computers and geotechnics, 2022.

[20] Zhang Q , Zhang X P , Wang H J , Zhang X Y, Li F Y, Xu D. Ground deformation induced by a shallow-buried twin-tunnel with small spacing: a case study of Guangzhou Metro Line 18 excavated by earth-pressure balance TBM[J].Environmental earth sciences, 2023.

[21] Boyang Zhang,Su-Mei Li. Stereoscopic image quality evaluation method applying deep limit learning machine[J]. Small Microcomputer Systems, 2017, 38(11):5.

[22] Li Shiyao,Zhou Liang,Liu Hu. Hazard source identification algorithm HIELM based on deep extreme learning machine[J]. Computer Science, 2017, 44(5):6.

[23] Dehghani M , Trojovsk P .Hybrid leader based optimization: a new stochastic optimization algorithm for solving optimisation applications[J]. Scientific Reports, 2022, 12(1):1-16.

[24] Yang Shuo, Luo Mingliang, Lin Yebin, Huang Jin, Jiang Jiayan. Quantitative study of factors affecting the interpolation accuracy of temperature data[J]. Shaanxi Meteorology, 2023(5):67-73.

[25] Thakur R , Rohilla R .An effective framework based on hybrid learning and kernel principal component analysis for face manipulation detection[J]. Signal, Image and Video Processing, 2024, 18(5):4811-4820.

[26] Yang J , Shen K , Pan S , Wang S, Zou Z. Study on the Deformation Mechanism of a Soft Rock Tunnel[J]. Fluid Mechanics and Materials Processing(English), 2022(002):018.