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# A reliable model for predicting the settling of soft soil subgrade to ensure highway safety

This paper introduces a new approach to managing subgrade settlement through finite element inverse analysis, focusing on creep effects in soft soil. Using MATLAB to connect Abaqus with an Improved Whale Optimisation Algorithm (IWOA) allows researchers to effectively extract calculation parameters for soft soil layers. The simulation of settlement deformation in subgrade soil, with due consideration of the creep effect, is achieved through the use of the modified Drucker–Prager yield criterion model and the time hardening creep law coupling model. The innovative approach enhances the Whale Optimisation Algorithm’s ability to avoid local extrema stagnation and improves the overall optimisation process. The IWOA was evaluated on 16 benchmark functions and compared with six other AI algorithms. Its effectiveness in global function performance was analysed using the Friedman test on the mean values from 30 simulation results. The evidence suggests that IWOA performs exceptionally well. Thereafter, the proposed method’s effectiveness was confirmed by developing a finite element inversion model for a highway subgrade on soft soil. The model was used to simulate subgrade deformation throughout construction, allowing for a comparison with experimental data to validate its reliability. The outcomes demonstrate a clear correlation between subgrade deformation from inversion analysis and real-world data. It is projected that, for the next 10 years, the post-construction settlement will be limited to a maximum variation of 10 cm. These projections have the potential to offer valuable theoretical insights for improving the efficiency of highway management and maintenance.

**Significance:**

The settlement deformation of soft soil subgrade under the stress of its own weight involves both elastic deformation and creep effect caused by the filling material. This, in turn, affects the stability and bearing capacity of highways. The precise forecasting of settlement in soft soil foundations and the guarantee of secure highway operation hold significant importance in theoretical research and provide valuable engineering guidance. This study introduces a novel method that employs an IWOA to create an inversion analysis model for subgrade settlement. This model incorporates the phenomenon of soil creep, which enhances the accuracy of predicting settlement behaviour.

## Introduction

Highway stability and bearing capacity are affected by elastic deformation and creep effect from infill material in soft soil subgrade under self-weight stress. Due to the characteristics of soft soil roadbeds, problems of overpass and pipe damage often occur, and the construction cost is high after settlement. Therefore, determining the settlement rules and influencing factors of roadbed engineering settlement under typical conditions, deducing the settlement forecast formula, and providing a reference and basis for geotechnical engineers have become the problems we urgently need to solve. In order to determine the causes and influencing factors of roadbed settlement, a series of real and model experiments must be carried out.<sup>1,2</sup>

One of the most significant problems in the construction and operation of roads built on soft soil is the creep settlement of the roadbed. Once soft soil is compressed by embankments, long-term and large enough settlement may occur due to the long-term creep behaviour of the soil. Therefore, the calculation of large deformation and failure time is very important for dealing with the design and construction of embankments on soft soil. The hardening-softening-hardening model has been widely used for the evaluation of long-term deformation in laboratory tests. In many empirical and semi-empirical design guidelines, the relationship of long-term settlement and secondary consolidation of soft soil is dependent on the laboratory one-dimensional compression creep test.

The interplay between computational modelling and optimisation techniques has transformed civil engineering practices, particularly in the analysis of soft soil layers. As urbanisation accelerates, accurately characterising these challenging geotechnical environments is crucial for the stability and safety of infrastructure projects. Traditional methods of soil analysis often prove cumbersome and inefficient, leading to a pressing need for innovative approaches that can streamline the process. In this context, the integration of the Abaqus finite element software with a Whale Optimisation Algorithm (WOA) using MATLAB presents a promising solution. This hybrid methodology not only enhances the rapid acquisition of computational parameters but also improves the precision of predictive models.<sup>3</sup> By leveraging advanced algorithms and robust modelling software, engineers can better understand elastic deformation and creep effect from infill material in soft soil subgrade under self-weight stress, ultimately informing design decisions and mitigating potential structural failures. Consequently, we aimed to explore these advanced techniques and their implications for modern civil engineering practices.<sup>4,5</sup>

## Material and methods

This paper details a complex approach in geotechnical engineering for modelling long-term subgrade settlement, utilising the Modified Drucker–Prager Cap Model to effectively capture the soil’s pressure-dependent yielding and plasticity. The model was paired with a time-hardening creep law to account for the accumulation of time-dependent

strain (creep), facilitating accurate simulations of soil consolidation and long-term deformation. This combination proficiently models soil behaviour under load, incorporating both immediate plastic settlement and gradual creep settlement over time, as implemented in the FEM software Abaqus.<sup>6,7</sup> This technique captures intricate soil behaviours, including plastic yield, volumetric hardening and time-dependent creep, which simpler models often overlook. It is crucial for predicting the long-term stability and serviceability of structures like roads, railways and foundations. This approach is implemented in FEM tools to assess complex scenarios, such as preloaded foundations, where both hardening and creep are of significant importance.

### Inverse analysis method of subgrade considering creep

#### Constitutive model of coupled creep effect

##### Soil stress state

We used the linear Drucker–Prager yield criterion hardening model. The equation for this model is:

$$\sigma_1 - \sigma_3 + \frac{\tan\beta}{2 + \frac{1}{3}\tan\beta}(\sigma_1 + \sigma_3) - \frac{1 - \frac{1}{3}\tan\beta}{1 + \frac{1}{6}\tan\beta}\sigma_c^0 = 0 \quad \text{Equation 1}$$

Principal stresses are denoted by  $\sigma_1$  and  $\sigma_3$ , with  $\beta$  representing the linear yield surface inclination,  $\tan\beta = \frac{6 \sin\varphi}{3 - \sin\varphi}$ , initial yield stress  $\sigma_c^0 = 2c \frac{\cos\varphi}{1 - \sin\varphi}$ ,  $\varphi$  is the internal friction angle and  $c$  is cohesion.

##### Calculation of creep process

In Abaqus, power law and hyperbolic sine law characterise creep qualities. A power law model includes time and strain hardening. We used Abaqus’s time hardening creep model to evaluate subgrade deformation.<sup>8</sup>

$$\dot{\varepsilon}^{cr} = A(\bar{\sigma}^{cr})^n t^m, \quad \text{Equation 2}$$

where  $\dot{\varepsilon}^{cr}$  is the comparable creep strain rate,  $\dot{\varepsilon}^{cr} = \frac{\Delta\varepsilon}{\Delta t}$ ,  $t$  is time,  $m$  controls the effect of time on creep,  $n$  controls the effect of stress, and  $A$  controls soil creep, which reflects soil composition and structure, and  $\bar{\sigma}^{cr}$  is the equivalent creep stress.

Combining time integration on both sides of Equation 2 yields:

$$\varepsilon = \frac{A}{m+1} (\bar{\sigma}^{cr})^n t^{m+1}, \quad \text{Equation 3}$$

Next, we calculate both sides’ logarithms:

$$\ln \varepsilon = \ln \frac{A}{m+1} + n \ln \bar{\sigma}^{cr} + (m+1) \ln t, \quad \text{Equation 4}$$

In Equation 4,  $\varepsilon$  represents soil strain at time  $t$ . In data analysis,  $n$  represents the power function in the  $\varepsilon$ - $\sigma$  relationship curve, whereas  $m+1$  represents the  $\varepsilon$ - $t$  relationship curve. The value of  $m+1$  varies from 0 to 1, indicating that  $m$  is between -1 and 0.  $A = \varepsilon(t, \sigma)$  shows the theoretical link between  $A$  and variables  $t$  and  $\sigma$ . At  $\sigma = 1$  and  $t = 1$ ,  $A/(m+1)$  represents strain. To calculate the natural logarithm of  $A/(m+1)$ , locate the junction of the  $\ln\varepsilon$ - $\ln\sigma$  curve with the axis extending to  $\ln\sigma = 0$ . Equation 3 shows the constitutive link between soil creep parameters  $m$ ,  $n$  and  $A$ .

### Soft soil subgrade consolidation and creep settlement calculation

#### Overview of calculation model

We used numerical modelling to analyse the settling effects of a highway through soft soil. Figure 1 shows asphalt pavement on the highway subgrade. From top to bottom, the model has 0.69 m asphalt pavement, 4 m embankment, 0.5 m sand cushion, and 19.5 m silty clay. Groundwater is 1 m below the surface. The embankment and pavement have a grade ratio of 1:1.5. Three deformation monitoring sensors were buried at measuring locations 1, 2, and 3 to track foundation deformations during construction.

#### Finite element model

The finite element model was used to calculate soft soil subgrade settling deformation. Model mesh size ranged from 0.75 m to 1 m.

#### Model calculation parameter inversion interval

The inversion process involves seven factors: elastic modulus  $E$ , Poisson’s ratio  $\mu$ , linear yield surface slope angle  $\beta$ , starting yield stress  $\sigma_c^0$ , and creep parameters  $A$ ,  $m$  and  $n$ . Table 1 specifies the range of values for each. The maximum iterations for WOA are 150, the population size is 30, and the logarithmic spiral form constant is 1.<sup>9,10</sup>

## Results and discussion

### Experimental tests and analysis

After applying these approaches, 16 classical benchmark test functions were used to evaluate the optimisation performance of the Improved Whale Optimisation Algorithm (IWOA). A comparative analysis was conducted on 30-dimensional and 100-dimensional assessments

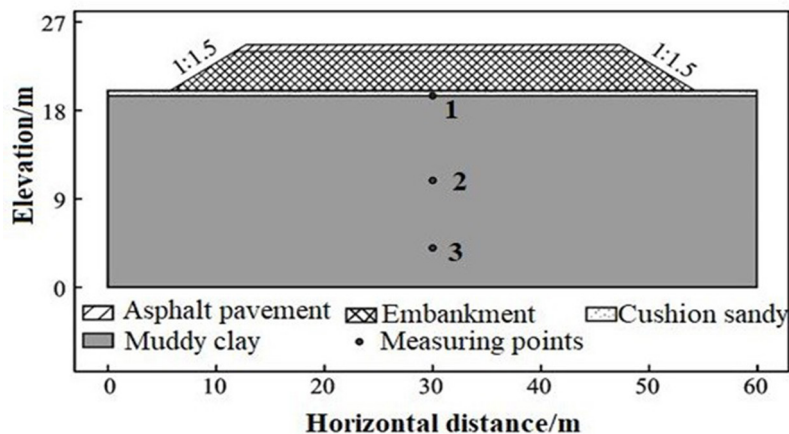


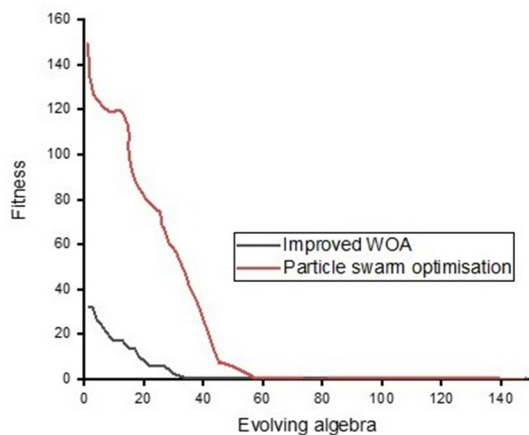
Figure 1: Design profile of highway subgrade.

**Table 1:** Ranges of the unknown inversion parameters

Model parameters to be inverted	Inversion interval
Elastic modulus E/kPa	[3000,5000]
Poisson's ratio $\mu$	[0.2,0.4]
Slope angle $\beta$ of the linear yield surface	[20,40]
Initial yield stress $\sigma_c^0/kPa$	[30,80]
Creep parameters	A $[1e^{-6},2e^{-6}]$
	m $[-1,0]$
	n $[1,3]$

**Table 2:** Comparisons between the inversion parameters

Model parameters	Parameters obtained by inversion	Design parameters
Elastic modulus E/kPa	4200	3300
Poisson's ratio $\mu$	0.36	0.25
Slope angle $\beta$ of the linear yield surface	35.3	22
Initial yield stress $\sigma_c^0/kPa$	57.0	45
Creep parameters	A $1.2e^{-6}$	$1.5e^{-6}$
	m $-0.99$	$-0.95$
	n $2.0$	$1.5$



**Figure 2:** Optimisation curves of the Particle Swarm Optimisation Algorithm and Improved Whale Optimisation Algorithm (IWOA).

using six distinct algorithms. The mean and standard deviation of the six algorithms were used to assess IWOA performance.<sup>11</sup> In addition, convergence plots and interval box plots for each technique in 30 dimensions showed IWOA's convergence behaviour and stability. Experiments confirmed that the three techniques in the original algorithm showed significant improvements.

### Engineering application based on IWOA

IWOA excels at evaluation tasks. However, the algorithm's main goal is optimisation. Restrictions make it harder for IWOA to solve complex optimisation problems in real-world circumstances than in test functions, but real-world optimisation is a true test of the algorithm's performance. Therefore, we used IWOA in a real engineering situation to test its efficacy.

Settlement measurements from survey points 1, 2 and 3 on the 210th day of construction were used to generate the fitness function in parameter inversion analysis. Figure 2 shows the fitness function convergence curve for inversion analysis for standard Particle Swarm Optimisation (PSO) and IWOA. The graph shows that the algorithm attained convergence because IWOA's fitness value remains unchanged in the 38th generation. Current fitness function is  $2.5e^{-5}$ . The 75th generation of PSO maintains fitness, with the fitness function value reaching  $4.7e^{-2}$  following convergence. Compared to PSO and other algorithms, IWOA has faster convergence, better optimisation and higher accuracy. Thus, the improved algorithm suggested in this research for inverse analysis can cut computing time and ensure highly accurate calculation results. The foundation constitutive model parameters from inverse analysis are shown in Table 2. It is clear that inversion analysis model parameters differ from design parameters.

Finite element calculation using model parameters from the inverse analysis yielded the vertical displacement cloud chart of the subgrade

in Figure 3a and 3b. The first chart shows the subgrade a few days after construction, whereas the second depicts its vertical displacement 10 years later. The diagrams illustrate that the subgrade's vertical displacement contour is an ellipse, with the largest settlement area at the centre of the foundation surface. The displacement cloud chart soon after construction is dramatically different from that a decade later. Due to its placement on soft soil, the roadway has visible later creep deformation. Thus, creep must be acknowledged and addressed to accurately calculate and predict highway deformation. Figure 4 shows the inversion and design parameter calculations for the whole construction period. Although they initially trend similarly, the figure shows that the difference between inversion parameter and design parameter results widens over time. Due to the high congruity between inversion analysis results and actual data, deformation computation accuracy can be considerably improved. This proves the method's reliability.

Calculations determined vertical settlement variations at the pavement centre point and on the road's shoulder (Figure 5a). After the highway's completion, the middle pavement settled more than the shoulder, as seen in the figure. Both locations show fast-to-slow deformation rates. After a decade, pavement settlement is below 10 cm, meeting highway subgrade design criteria. Figure 5b shows how to calculate uneven settlement by comparing the settlement values of the pavement centre and shoulder over time. Time shows that the unequal settling value gradually stabilises about 5 years after construction. The stabilising process ensures that the average settling value remains at 16 mm.

### Conclusion

The primary goal of IWOA is to solve the optimisation problem, although it demonstrates exceptional performance in dealing with test functions. Real-world optimisation problems are more intricate and involve constraints, which pose a greater challenge for IWOA to solve. To this end, a novel approach used in this study tackled subgrade settlement using finite element inverse analysis, with a specific emphasis on the influence of creep in soft soil. Using MATLAB programming language to integrate Abaqus FEA software with IWOA, one can precisely and effectively derive calculation parameters for soft soil layers. The new method not only enhances WOA's ability to avoid local extremum stagnation during subsequent iterations, but also aims to enhance the optimisation process. The revised algorithm underwent testing on a highway subgrade located in an area characterised by soft soil in order to verify its effectiveness and suitability. We developed a subgrade settlement inversion analysis model using IWOA. This model more accurately represents the settlement behaviour by considering the creep effect of soft soil. A highway through an area with very soft soil was the subject of a numerical simulation study to verify the efficacy of the suggested model. Results from inversion analysis on the project's base model parameters show that the improved algorithm outperforms the standard PSO algorithm in terms of optimisation speed and accuracy. A strong degree of agreement regarding subgrade deformation was revealed by comparing the measured data with the inversion analysis results, thus confirming the dependability and rationale of the approach suggested in this paper. Parameters for the calculations were derived from inversion

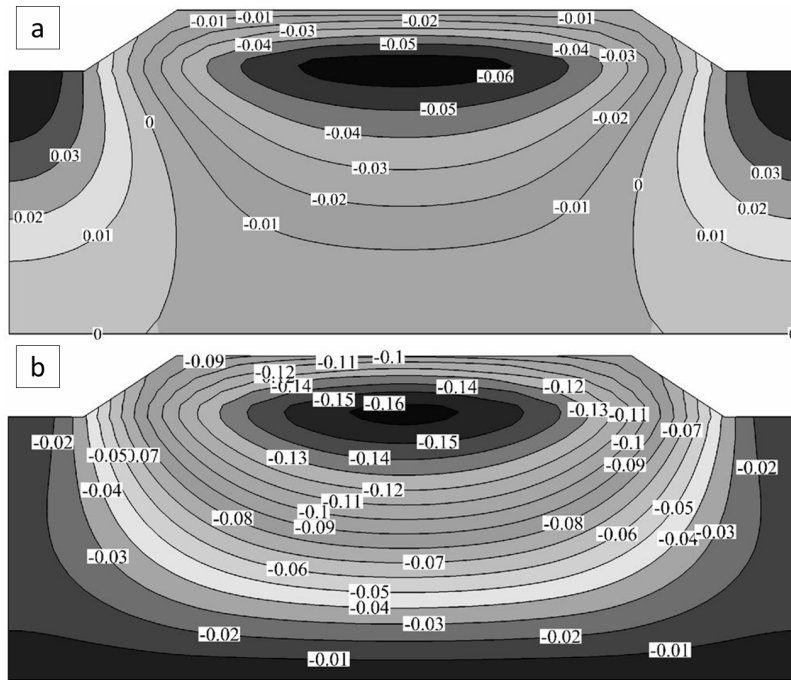


Figure 3: Contour of vertical displacement of subgrade: (a) subgrade just after completion and (b) subgrade 10 years after completion.

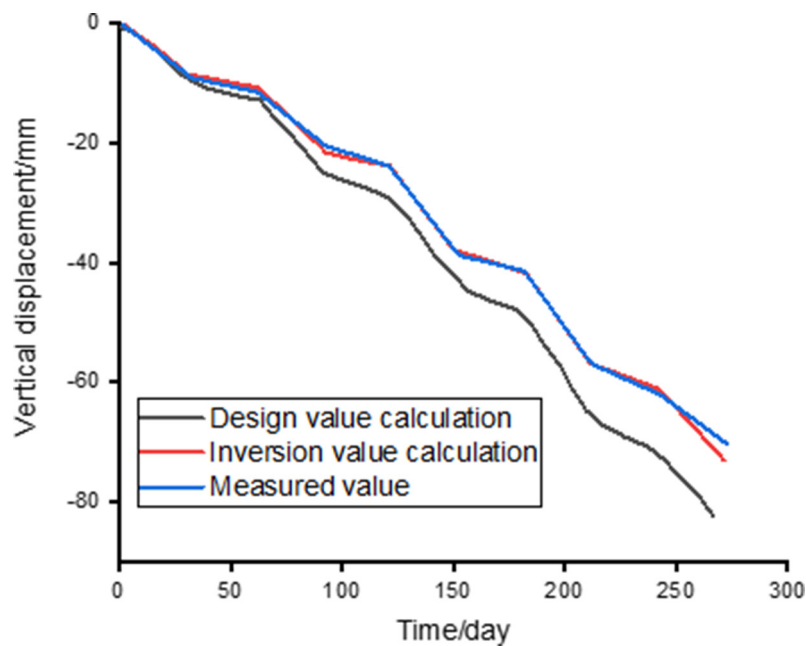


Figure 4: Calculated and measured settlement findings.

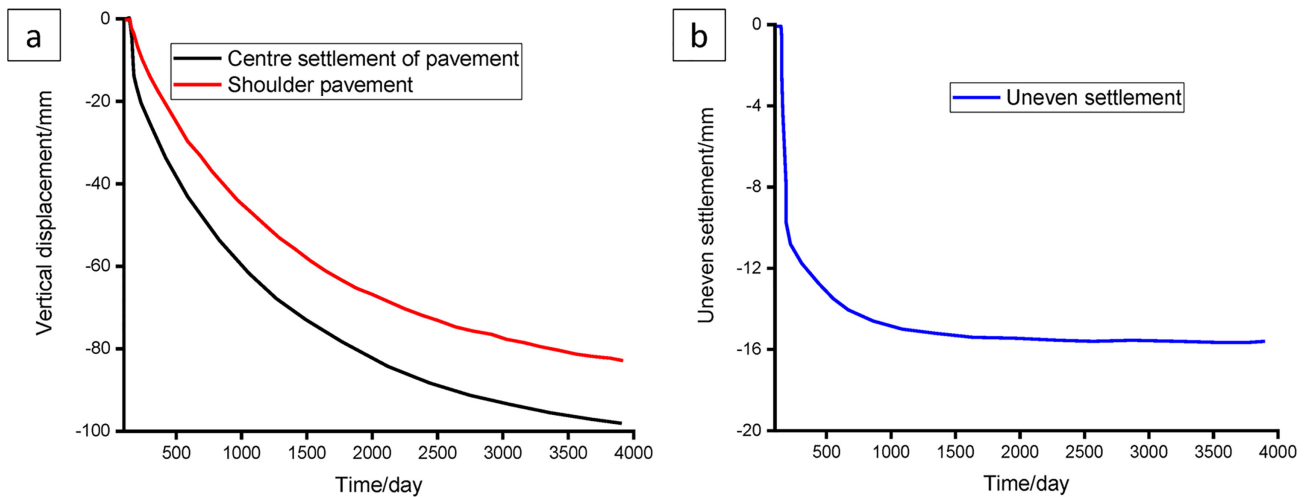
analysis to predict how much the subgrade and pavement would settle after 10 years of construction. The results demonstrate that the enhanced algorithm is the most cost-effective and has a clear path. It is clear that incorporating various strategies enhances the precision and consistency of the fundamental WOA. When it comes to highway management and operation, this forecast provides substantial theoretical support. Also, other projects that are comparable to this one can use the results of this research paper as a reference.

### Data availability

The data used to support the findings of this study are included within the article.

### Declarations

We have no competing interests to declare. We have no AI or LLM use to declare.



**Figure 5:** Subgrade settlement time-varying trend: (a) pavement and shoulder settlement and (b) subgrade deformation.

## Authors' contributions

S.M.M: Conceptualisation, methodology, formal analysis, validation, data curation, writing – original draft, writing – review and editing. P.F.N.: Investigation, formal analysis, data curation, project administration. M.P.T.F.: Investigation, formal analysis, validation, supervision, project leadership. S.E.A.: Methodology, investigation, supervision, writing – review and editing. All authors read and approved the final manuscript.

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