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Study on wetting deformation model of coarse-grained materials based on P-Z model and BP neural network

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The wetting deformation of coarse-grained materials can seriously affect the safety of earth and rock dams during initial water storage. The wetting model formulas are expressed in various forms and have complex parameters. Only a small amount of test data is fitted by mathematical statistics, and the universality of the obtained wetting model is unknown. Duncan-Chang E-B constitutive model cannot accurately reflect the wetting deformation characteristics of coarse-grained materials. Through the double-line wetting test of coarse-grained materials, the wetting model proposed by predecessors was verified and analyzed. Based on the indoor wetting test data, the parameters of each wetting model were fitted to analyze the accuracy of each wetting model in describing the wetting deformation characteristics. According to the P-Z model in the elastic-plastic theory and the wetting model formula, the P-Z wetting model is established, and the BP artificial neural network is introduced to establish the artificial neural network wetting deformation prediction model based on the P-Z model. The results show that the relationship between wetting axial strain and wetting stress level is best expressed by the exponential function. The relationship between wetting volumetric strain and wetting stress level is best described by Cheng's linear function. The relative errors between the predicted and experimental values of the proposed neural network prediction model are all within 6%. The relationship between wetting axial strain and wetting stress level is exponential function, and the relationship between wetting volumetric strain and wetting stress level is linear function. The P-Z wetting model proposed in this research can better reflect the wetting deformation characteristics of coarse-grained materials under complex stress paths. The artificial neural network prediction model based on P-Z wetting model is more reliable and accurate, which can meet the prediction requirements of actual engineering for wetting deformation of coarse-grained materials.

KEYWORDS

coarse-grained materials, triaxial wetting test, wetting deformation model, P-Z model, BP neural network

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1 Introduction

The wetting and deformation of coarse-grained materials can lead to uneven settlement, cracks, and collapse of the dam during impoundment periods (Jia et al., 2020; Zhang et al., 2022), rainfall infiltration, and other processes. Severe wetting and deformation can increase the risk of dam failure (Ge et al, 2020; Wang et al, 2022), with serious implications for the safe operation of the dam as well as downstream areas (Wu et al, 2021; Ge et al, 2022; Wang et al, 2023). For example, when the Pubugou Rockfill Dam (Lin et al., 2017) was impounded to a high water level, When Laos sangpian reservoir (Xu, 2018) was impounded to a high water level, and when the Guanyinyan Composite Dam (Jia et al., 2018) was impounded for the first time, the coarse-grained materials both underwent significant wetting, resulting in uneven settlement and cracks in the dam (Jie et al., 2019), so it is especially important to research the wetting deformation of earth-rock dams. Cheng et al. (2010), Chi and Zhou (2017), Chen, (2019), and Zhou et al. (2019) fitted the empirical formula of the wetting model based on the test data on the basis of the triaxial wetting test. The functional relationship between wetting axial strain and wetting stress level is mainly summarized as an exponential, hyperbolic and linear function, while the functional relationship between wetting volumetric strain and wetting axial strain is basically a linear function. Wei and Zhu (2007) investigated the wetting stress-strain relationship of coarse-grained soils through a modified triaxial apparatus and suggested a double-line method test. In terms of the constitutive model, Ding and Qian (2022) proposed an improved wetting deformation model by the Duncan-Chang E-B model. Since the Duncan-Chang *E-B* model cannot reflect the complex stress path and the influence of stress on deformation, the fitting effect with the test results is not good. The P-Z model based on the generalized plastic model can well reflect the complex stress path correlation of the wetting deformation of coarse-grained materials (Zou et al., 2013), and more accurately simulate the wetting deformation law of coarse-grained materials.

However, the wetting models proposed by predecessors are different, and they are basically fitted by a small amount of data through mathematical statistics on the basis of some coarse-grained material experiments, which have problems such as low model accuracy, too many fitted parameters and complex expressions, and significant differences in results.

In this research, based on the wetting test data, the parameters of each wetting model are fitted and the wetting deformation is compared and analyzed to determine a more universal wetting strain model. The P-Z principal constitutive model is also combined with BP neural network to establish an artificial neural network wetting deformation prediction model based on the P-Z model, overcoming the problems of complex and heavy workload in the triaxial wetting test process and the inaccuracy of wetting deformation data due to the uncertainty in the test and numerical simulation stages.

2 triaxial wetting test

2.1 Test gradation

According to the standard of the geotechnical test method, the actual dry density of the materials used in the test was calculated to be 1.58×10^3 kg/m^3, and the relative density is 0.56. The content of each particle size group is shown in Table 1, and the gradation curve is shown in Figure 1.

TABLE 1 Content of each particle size group.

Particle size(mm)	50~40	40~30	30~20	20~10	10~5	<5
Content (%)	16.6	11.8	18.9	23.8	18.9	10.0

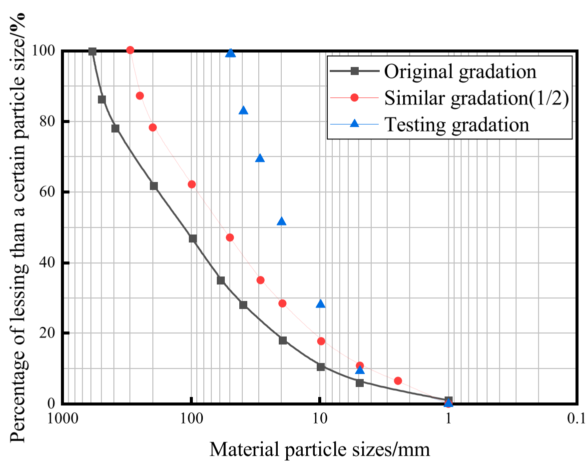

FIGURE 1
Original grading and test grading curves.

2.2 Triaxial test plan

The test was set under three confining pressure conditions of 800kPa, 1,600kPa, and 2,400 kPa, and five wetting stress levels of 0, 0.2, 0.40, 0.60, and 0.80 were set at each group of confining pressure. The wetting stress level is the ratio of the peak deviatoric stress in the wetting stage to the peak deviatoric stress in the conventional triaxial test, i.e., $s = (\sigma_1 - \sigma_3)/(\sigma_1 - \sigma_3)_f$. In this research, the conventional triaxial shear test of coarse-grained materials is first carried out. Then the peak deviatoric stress of specimen failure under confining pressure of 800kPa, 1,600kPa and 2,400 kPa is measured. Based on this, the stress levels of 0,0.2,0.40,0.60 and 0.80 are set, so that the corresponding deviatoric stress at each stress level can be calculated. In the test, the

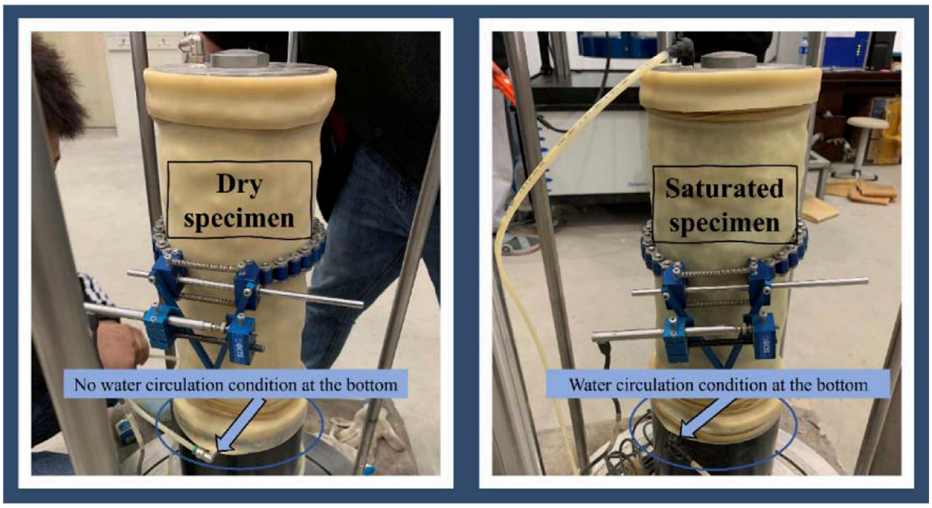

FIGURE 2
Comparison of dry and saturated specimens.

FIGURE 3
Comparison of coarse-grained materials in the dry state and saturated state.

effect of maintaining the level of wetting stress is achieved by keeping the numerical level of the deviatoric stress of the triaxial instrument constant. To reduce the influence of creep of coarse-grained materials, the material with initial water content of 5% is selected and the "double line method" is selected as the wetting test method (Miao, 2018; Jia et al., 2019). The strain difference between the wetting shear curve and the dry shear test curve under the same stress state is taken as the wetting deformation value under this stress state. Although the wetting volumetric strain obtained by this method is slightly larger, the prediction of deformation is safe and reasonable.

2.3 Test results

The results of the conventional triaxial test and wetting triaxial test of coarse-grained materials are shown in Figures 2, 3. The test values of wetting axial strain and wetting volumetric strain corresponding to the wetting deformation test are listed in Table 2.

3 Wettung model analysis and validation

3.1 Wetting axial strain model

At present, the functional relationship between wetting axial strain and wetting stress level is mainly hyperbolic function, exponential function, and linear function (Sun et al., 2023). To investigate the extent to which the level of wetting stress and the confining pressure affect the wetting axial strain and to compare the suitability of each wetting model to the test data. In this research,

TABLE 2 Wetting deformation of coarse-grained materials.

σ_3/kPa	S_L	ε_a/%	ε_v/%
800	0	0.03	0.05
	0.2	0.06	0.09
	0.4	0.12	0.22
	0.6	0.32	0.35
	0.8	0.70	0.40
1,600	0	0.05	0.13
	0.2	0.11	0.20
	0.4	0.21	0.34
	0.6	0.43	0.43
	0.8	0.80	0.51
2,400	0	0.08	0.18
	0.2	0.14	0.29
	0.4	0.26	0.48
	0.6	0.50	0.56
	0.8	0.82	0.64

TABLE 3 Fitting parameters of exponential function type I.

Parameters	k_1	b_1	k_2	b_2	Average fit $\overline{R^2}$
Numerical values	0.00391	−0.0047	−0.0831	4.7259	0.963

based on the results of the triaxial wetting test, the parameter fitting and wetting axial strain calculation of exponential function type, hyperbolic function type, and linear function type proposed by predecessors are carried out, respectively, and the best adaptation function is determined according to the results of comparative analysis.

(1) Expression for the exponential function relationship I (Cheng, et al., 2010):

$$\Delta\varepsilon_a = \left(k_1\frac{\sigma_3}{P_a} + b_1\right)e^{\left(k_2\frac{\sigma_3}{P_a}+b_2\right)S_L} \tag{1}$$

Where:
ε_a =wetting axial strain,
S_L =wetting stress level,
σ_3 =confining pressure, P_a is standard atmospheric pressure,
k_1, b_1, k_2, b_2 = material test parameters.

(2) Expression for the exponential function relationship II (Niu, 2020):

$$\Delta\varepsilon_a = f_1 e^{g_1\sigma_3 + \left(f_2\sigma_3+g_2\right)S_L} \tag{2}$$

Where:
f_1, g_1, f_2, g_2 = model parameters.

TABLE 4 Fitting parameters of exponential function type II.

Parameters	f_1	g_1	f_2	$\overline{R^2}$	Average fit $\overline{R^2}$
Numerical values	0.0152	0.0008	−0.000812	4.7053	0.965

TABLE 5 Fitting parameters of hyperbolic functions.

Parameters	K_1	A	K_0	m	Average fit $\overline{R^2}$
Numerical values	0.00274	0.385	0.0595	0.722	0.932

TABLE 6 Fitting parameters of linear functions.

Parameters	c	d	e	f	Average fit $\overline{R^2}$
Numerical values	0.00008	0.7567	0.00004	−0.108	0.911

(3) Expression for the hyperbolic function relationship (Chi and Zhou, 2017):

$$\Delta\varepsilon_a = \frac{\left[K_1\left(\frac{\sigma_3}{P_a}\right) + A\right]S_L}{1 - S_L} + \frac{1}{K_0}\left(\frac{\sigma_3}{P_a}\right)^m \tag{3}$$

Where:
K_1, A, K_0, m = model parameters.

(4) Expression for the linear functional relationship (Chen, 2019).

$$\Delta\varepsilon_a = (c\sigma_3 + d)S_L + (e\sigma_3 + f) \tag{4}$$

Where:
c, d, e, f = model parameters.

According to the triaxial wetting test data, the parameters of the above four function types are fitted. The fitting of each function model parameters and the determination coefficient of fitting $\overline{R^2}$ are shown in Tables 3–6. A comparison of the calculated and experimental values for each wetting axial variation model is shown in Figure 4. The results show that the model prediction curve of exponential function type I has the best fitting effect with the triaxial wetting test data, the fitting effect of hyperbolic function and exponential function type II is the second. The fitting effect of the linear function is the worst. Therefore, for the expression of the functional relationship between the wetting stress level and the wetting axial strain, the exponential function type I relational fitting of the wetting model has the highest accuracy. It is more in line with the test phenomenon. Its parameters are simple to derive and easy to calculate.

3.2 Wetting volumetric strain model

Zuo and Shen (1989) thought that the wetting volumetric strain was not related to the wetting stress level in the early stage, but was close to the hyperbolic relationship with the test confining pressure. With the progress of test instruments and

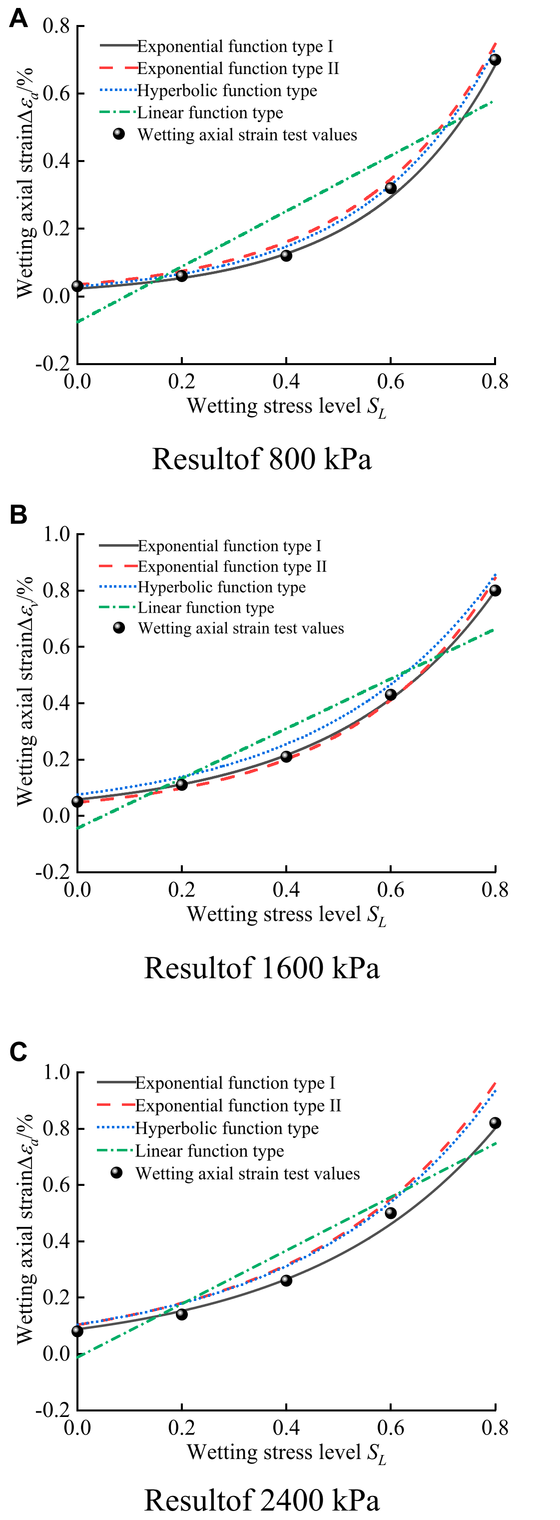

FIGURE 4
Comparison of simulation and test results of four wetting axial strain models. **(A)** Result of 800 kPa **(B)** Result of 1,600 kPa **(C)** Result of 2,400 kPa.

TABLE 7 Parameter fitting values of Cheng's linear model.

Parameters	k_3	b_3	k_4	b_4	Average fit $\overline{R^2}$
Numerical values	0.0022	0.4991	0.0111	−0.0545	0.992

research results, it is found that the wetting deformation of coarse aggregate under different stress paths is not the same, so there is a correlation between wetting volumetric strain and confining pressure and stress level. Cheng et al. (2010) considered that the wetting volumetric strain tends to vary linearly with the wetting stress level, and the relationship between wetting volumetric strain and wetting stress level was fitted by linear function expression (4 parameters):

$$\Delta\varepsilon_v = \left(k_3\frac{\sigma_3}{P_a} + b_3\right)S_L + k_4\frac{\sigma_3}{P_a} + b_4 \tag{5}$$

Where:
$\Delta\varepsilon_v$ = wetting volumetric strain,
S_L = wetting stress level,
σ_3 = confining pressure,
P_a = standard atmospheric pressure,
k_3, b_3, k_4, b_4 = material test parameters.

Zhou et al. (2019) introduced the average principal stress p and generalized shear stress q of the sample during the wetting process, deduced the method for calculating the ratio k of wetting volumetric strain to wetting axial strain, and summarized the wetting volumetric strain formula 6 parameters):

$$\Delta\varepsilon_v = \log_b\left(q/ap + b^3\right)\left\{\frac{\left[K_1\left(\frac{\sigma_3}{P_a}\right) + A\right]S_L}{1 - S_L} + \frac{1}{K_0}\left(\frac{\sigma_3}{P_a}\right)^m\right\} \tag{6}$$

Where:
a, b, K_1, A, K_0, m = material test parameters.

Peng et al. (2010) believed that the wetting volumetric strain is caused by spherical stress and partial stress, respectively. The relationship between the wetting volumetric strain caused by spherical stress and the confining pressure can be expressed by a hyperbola. The relationship between the wetting volumetric deformation caused by partial stress and the wetting stress level is fitted by linear and exponential functions. The wetting volumetric strain formula 6 parameters) is summarized as follows:

$$\Delta\varepsilon_v = a + b\left(\sigma_3/P_a\right) + \left[c\left(\sigma_3/P_a\right) + d\right]S_L + f\ln\left(\sigma_3/P_a\right) + g \tag{7}$$

Where:
a, b, c, d, f, g = material test parameters.

According to the triaxial wetting test data, the parameters of the wetting volumetric strain model of the above three function types are fitted. The fitting of each function model parameters and

TABLE 8 Parameter fitting values of Zhou's linear model.

Parameters	a	b	K_1	A	K_0	m	Average fit $\overline{R^2}$
Numerical values	2.9591	0.4365	0.00274	0.385	0.0595	0.722	0.983

TABLE 9 Parameter fitting values of Peng's linear model.

Parameters	a	b	c	d	f	g	Average fit $\overline{R^2}$
Numerical values	−0.01	0.0081	0.0072	0.4083	0.1462	−0.276	0.959

the determination coefficient of fitting $\overline{R^2}$ are shown in Tables 7–9. The comparison between the calculated values of each wetting volumetric strain model and the experimental values is shown in Figure 5. The results show that the prediction curve of Cheng's linear model fits the triaxial wetting test data the best; the Peng's function fits the second, and the Zhou's function fits the worst. Therefore, the Cheng's linear model has the highest accuracy in fitting the wetting volumetric strain model, and the Cheng's linear model is a 4-parameter; each parameter is easily derived from the test results, which is more concise and convenient than the 6-parameter models of Zhou and Peng.

4 BP neural network prediction model based on the P-Z model

4.1 P-Z wetting model

Zienkiewicz and Pastor proposed the generalized plasticity theory in 1985, then Pastor and Zienkiewicz extended their basic framework and on which they developed the constitutive model of soil, the Pastor-Zienkiewicz model (Pastor et al., 1985; Pastor et al., 1987) (hereafter referred to as the P-Z model).

The expression of the generalized plastic matrix of the P-Z model is:

$$D_{Lep} = D_e - \frac{D_e n_{gL} n^T D_e}{H_L + n_{gL}^T D_e n} \quad D_{Uep} = D_e - \frac{D_e n_{gU} n^T D_e}{H_U + n_{gU}^T D_e n} \tag{8}$$

Where:

L = loading,

U = unloading,

n_{gL} = direction vector of plastic potential,

n_{gU} = direction vector of plastic potential, meaning the direction of plastic strain increment,

n = loading direction vector, equivalent to the normal direction of yield surface,

H_L = the direction of plastic flow during loading, and represent the direction of plastic strain increment.

H_U = the direction of plastic flow during unloading, and represent the direction of plastic strain increment.

In the P-Z model, for each homogeneous material, the elastic matrix is determined by the bulk and shear modulus, which varies linearly with the mean stress.

$$K = K_{evo} p, G = G_{eso} p \tag{9}$$

Where:

K_{evo}, G_{eso} = the modulus of elasticity parameters.

The relationship curves of wetting stress level with wetting axial strain and wetting volumetric strain under different confining pressures are drawn by the wetting axial strain calculation model and the wetting volumetric strain calculation model determined in Section 2. In finite element numerical simulation, the corresponding confining pressure and stress level are calculated from the stress state of Gauss points of each element; through the interpolation calculation of the current confining pressure and stress level in the wetting calculation model, the wetting axial strain and wetting volumetric strain of each unit are obtained. The wetting deformation calculated by each unit is distributed to each strain component of the total strain of the current load step. The wetting deformation corresponding to each submerged unit is transformed into an equivalent nodal force applied to the sample, and the additional deformation is calculated as the wetting deformation.

4.2 Computational analysis of the P-Z wetting model

The finite element numerical simulation of the P-Z intrinsic model used in this research are carried out in the GEHOMadrid finite element program. The P-Z model framework is clear and easy to implement in finite element programs. The static and dynamic analysis process of soil structures can be completed with a set of parameters. According to Formula (8), Formula (9) and literature (Pastor et al., 1985; Pastor et al., 1987), there are 12 parameters in the P-Z constitutive model of coarse-grained materials, including eight dimensionless parameters: $M_g, M_f, \alpha_g, \alpha_f, \beta_0, \beta_1, H_0, \gamma_{DM}$, and four stress unit parameters: H_{u0}, γ_u, K_{evo}, G_{eso}. Where K_{evo}, G_{eso}, M_g, α_g, and H_0 can be determined by triaxial static tests, and the remaining 7 parameters can be determined from the above 5 parameters by derivation of empirical formulae. The calculation and optimization of the parameters of the P-Z model are described in detail by the author of the research (Zhang et al., 2019). Due to the limited space, this paper no longer lists the specific process of determining parameters. The calculation parameters of the P-Z model are shown in Table 10.

The GEHOMadrid finite element program was used to carry out numerical simulations of the wetting deformation of coarse-

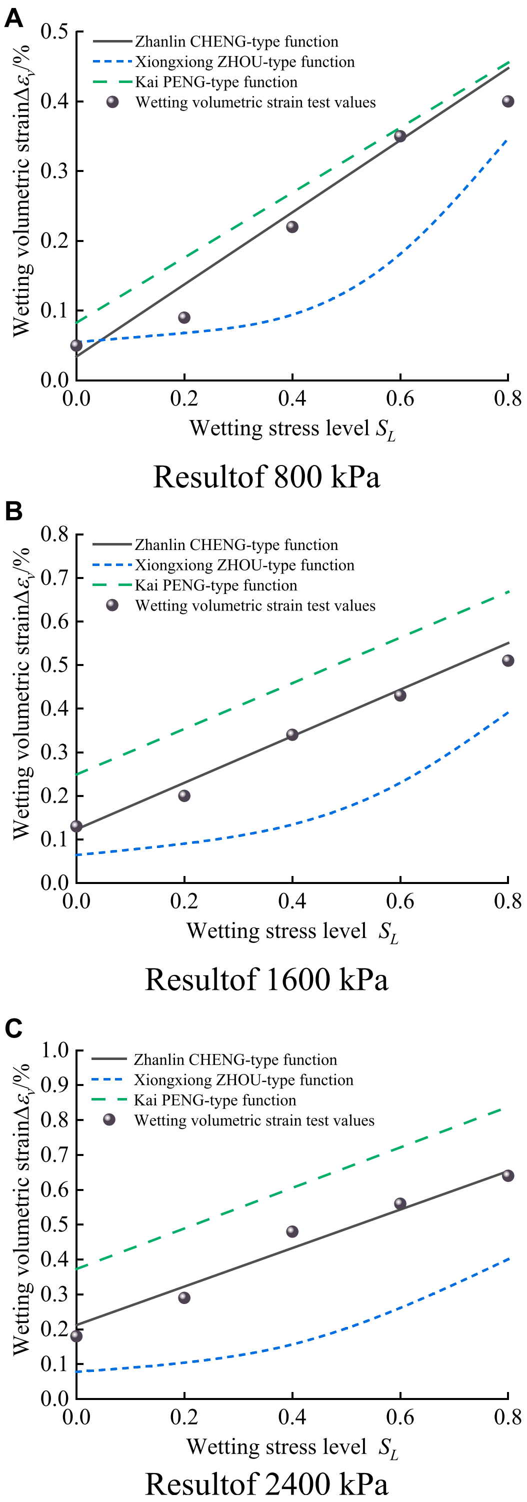

FIGURE 5
Comparison of simulation results and test results of three wetting volumetric strain models. **(A)** Result of 800 kPa **(B)** Result of 1,600 kPa **(C)** Result of 2,400 kPa.

grained materials. A cylindrical specimen with an internal diameter of 150 mm and a height of 300 mm was used in the triaxial wetting test. The finite element model of the specimen is shown in Figure 6, with a total of 1760 elements and 1983 nodes generated. Based on the P-Z wetting model, finite element simulations of triaxial compression tests are carried out on the

TABLE 10 Parameters of the P-Z constitutive model for coarse-grained materials.

Parameters	M_g	M_f	α_g	α_f	β_0	β_1
Numerical values	1.73	0.97	0.45	0.45	4.2	0.2
Parameters	H_0	γ_{DM}	γ_u/kPa	H_{u0}/kPa	K_{evo}/kPa	G_{eso}/kPa
Numerical values	34.83	0	0	0	5,581	18493.40

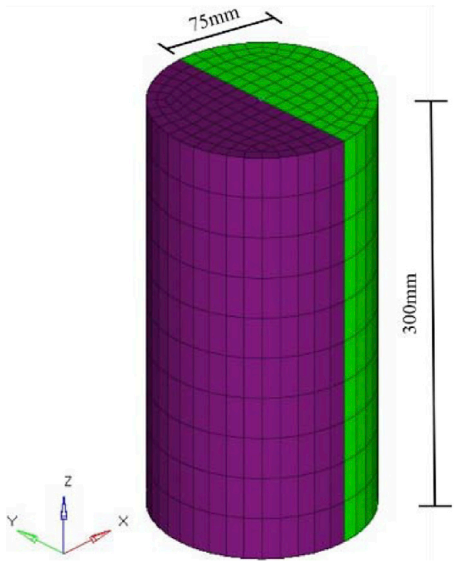

FIGURE 6
Simulation diagram of actual specimen for triaxial tests.

specimens. The simulation results are compared and analyzed with the triaxial test results to verify the rationality of the P-Z wetting procedure.

According to the standard for geotechnical test methods, when the axial strain of the specimen reaches 15% of the specimen height, it is considered a shear failure. The P-Z wetting program was used to numerically simulate three types of confining pressure conditions at 800kPa, 1600kPa, and 2400kPa, respectively. The calculated results of the simulated triaxial wetting test are shown in Figures 7, 8 shows the comparison between the triaxial wetting test and the numerical simulation results.

The comparison results show that the maximum axial strain error at 800 kPa is 9.5% and the maximum volumetric strain error is 8.6%; the maximum axial strain error at 1,600 kPa is 7.7%, and the maximum volumetric strain error is 9.1%; the maximum axial strain error at 2,400 kPa is 9.5%, and maximum volumetric strain error is 7.4%. With the increase of confining pressure, the error decreases gradually. The main reason is that before the axial strain reaches 10%, the deformation of the sample during the test is greatly affected by the factors such as rubber membrane embedding, which leads to the error of the data, but the error is in the range of 7.4%–9.5%, which is less than 10%. It shows that the P-Z model shows good adaptability to the stress-related properties of coarse-grained materials under complex stress paths and can better simulate the wetting deformation pattern of coarse-grained materials.

4.3 BP neural network wetted deformation prediction model

Based on the P-Z wetting model of coarse granular material, BP neural network is introduced to train the wetting test deformation and establish an artificial neural network (Zhang et al., 2021; Ju et al., 2005) wetting deformation model based on the P-Z model, which enables a better mapping of the non-linear relationship between wetting deformation of earth-rock dams and its influencing factors. It reduces the influence of systematic and chance errors in wetting deformation analysis. A three-layer BP neural network is selected, relying on increasing the number of nodes in the hidden layer to obtain a lower error. The input layer corresponds to the confining pressure and the wetting stress level, and the output layer corresponds to the wetting deformation. An empirical formula is used to determine the optimal number of nodes in the hidden layer, as shown in Formula (10). The topology and flow chart of the neural network wetting deformation model is shown in Figures 9, 10.

$$h = \sqrt{m+n} + a \tag{10}$$

Where:

h = the number of nodes in the hidden layer, m, n = the number of nodes in the input and output layers,

a = a regulation constant between 1 and 10.

Based on the P-Z wetting model, a total of 60 sets of wetting axial strain and wetting volumetric strain data at five wetting stress levels of 0,0.2,0.4,0.6 and 0.8 under 12 confining pressure conditions of 200 kPa, 400 kPa, 600 kPa, 800 kPa, 1,000 kPa, 1,200 kPa, 1,400 kPa, 1,600 kPa, 1800 kPa, 2000 kPa, 2,200 kPa and 2,400 kPa are used as training samples. The first 50 groups are used as the training set and the last 10 groups are used as the testing set. When the network training is iterated 95 and 98 times, the error cost function is satisfied, and the convergence process at the end of training is shown in Figure 11.

Figure 12 is the comparison between the experimental values and the predicted values of wetting deformation under five wetting stress levels with different confining pressures and the relative error of the prediction model. From Figure 12, it can be seen that the absolute error of the wetting axial strain prediction is in the range of

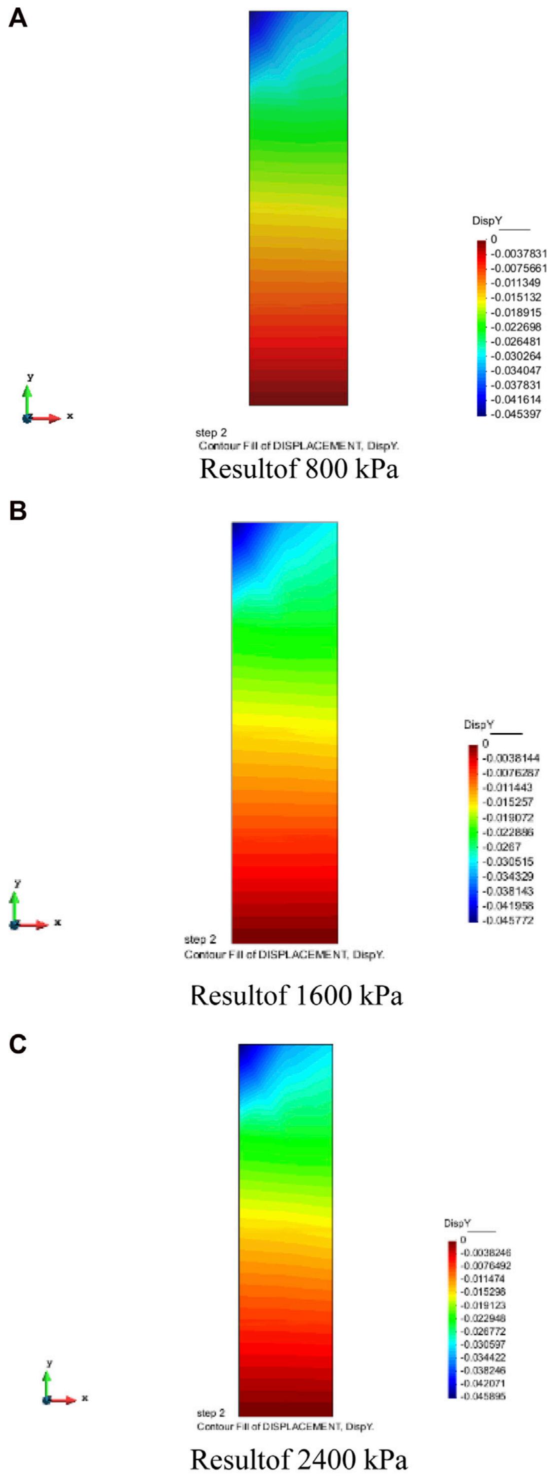

FIGURE 7
Simulation diagram of P-Z wetting model **(A)** Result of 800 kPa **(B)** Result of 1,600 kPa **(C)** Result of 2,400 kPa.

0.00086%–0.033%, with an average error of 0.011%, and the relative error is controlled within 1.041%–6.980%, with an average relative error of 4.094%, which are basically control within7%. The absolute error in the prediction of wetting volumetric strain ranged from 0.0029%–0.0115%, with an average error of 0.0122%, and the relative error is basically controlled within 0.5800%–5.872%, with an average relative error of 3.671%, which are basically controlled within 6%. This is due to the fact that the initial weights of the neural

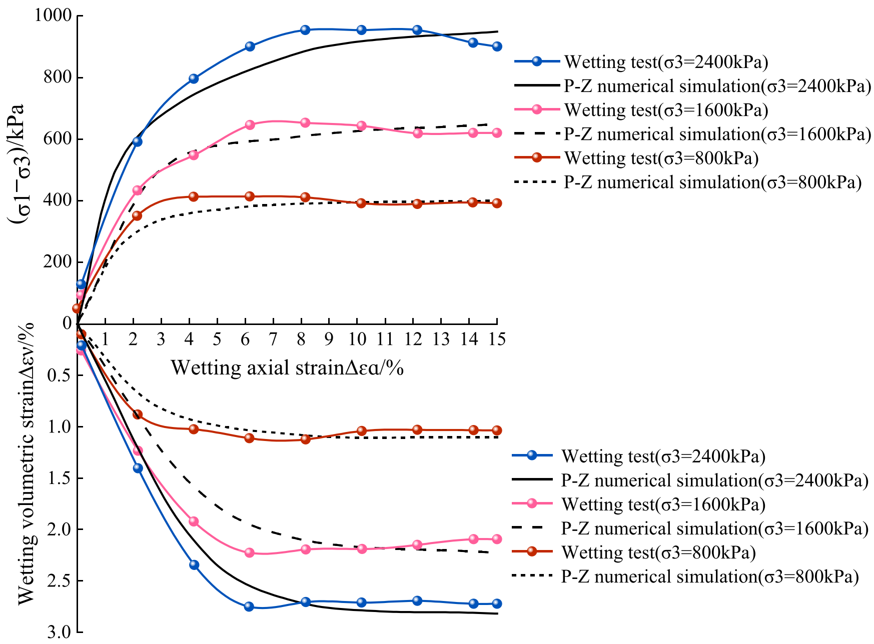

FIGURE 8
Comparison of simulation results and test results of the P-Z wetting Model.

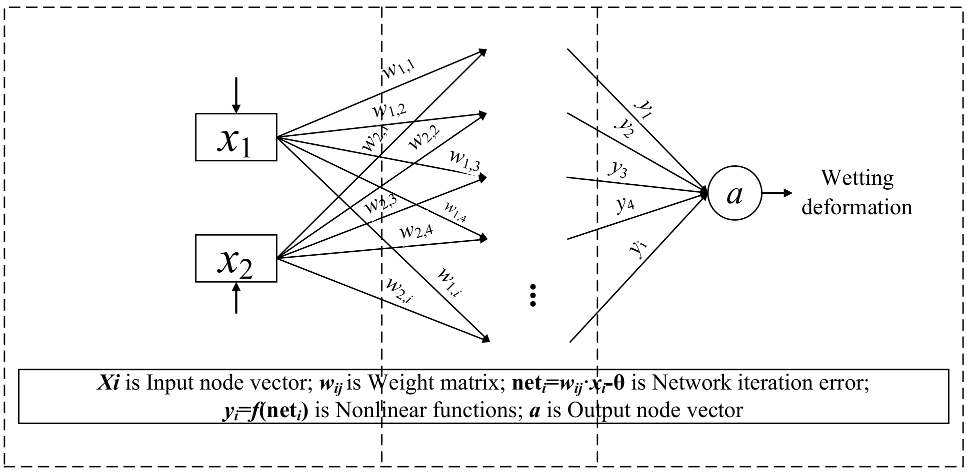

FIGURE 9
BP neural network topology.

network are randomly given, and the number of training sessions and the final weights will be slightly different each time, as well as the fact that there are human errors in the finite element numerical simulation and test conditions and test methods based on the P-Z model, resulting in differences between the prediction results and the test results. The relative error of the prediction model in this paper is basically controlled within 6%, so it can be considered that the neural network model is more reliable and accurate, which can meet the accuracy requirements for the prediction of wetting deformation.

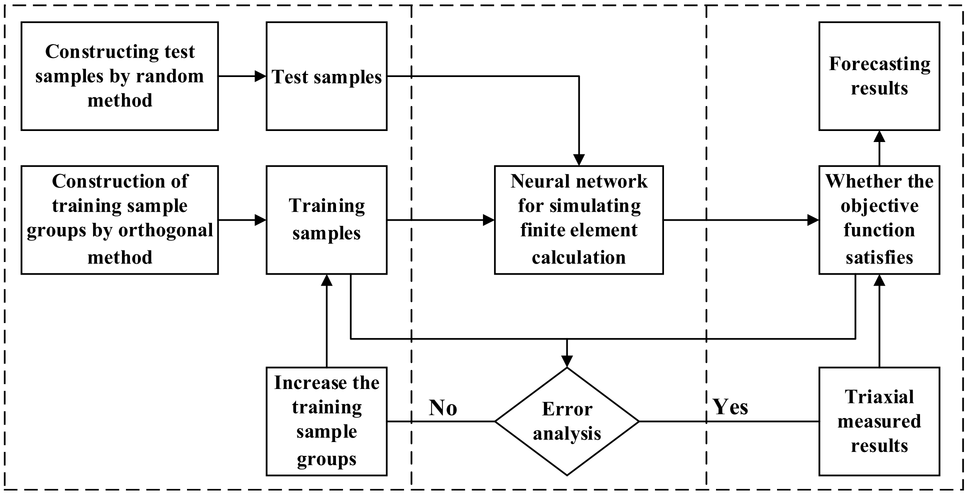

FIGURE 10
Analysis method of wetting deformation prediction model of BP neural network.

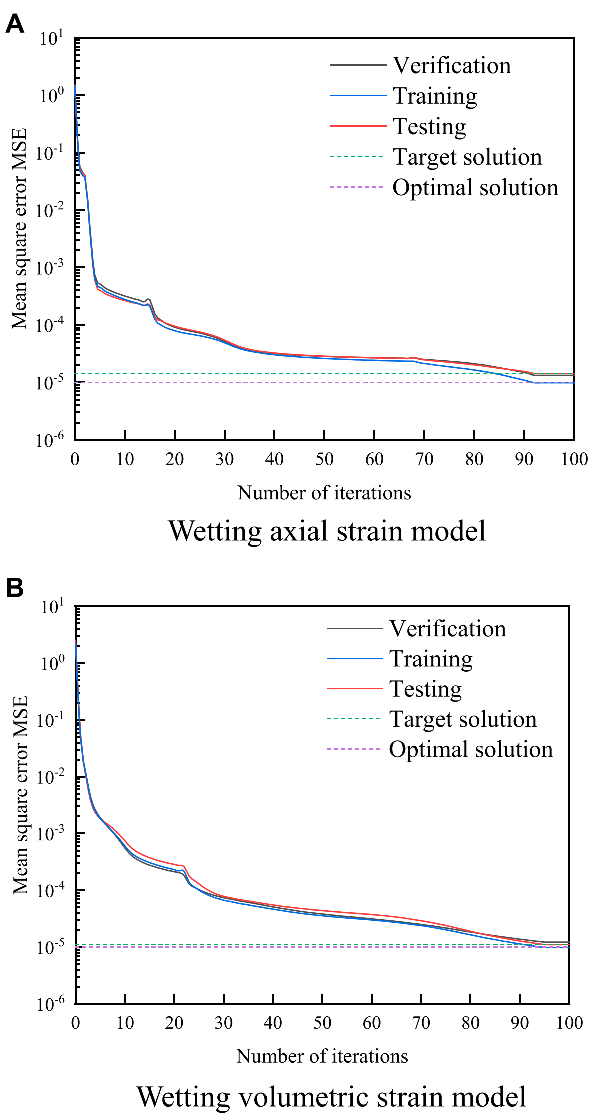

FIGURE 11
Iterative process of wetting prediction model. **(A)** Wetting axial strain model **(B)** Wetting volumetric strain model.

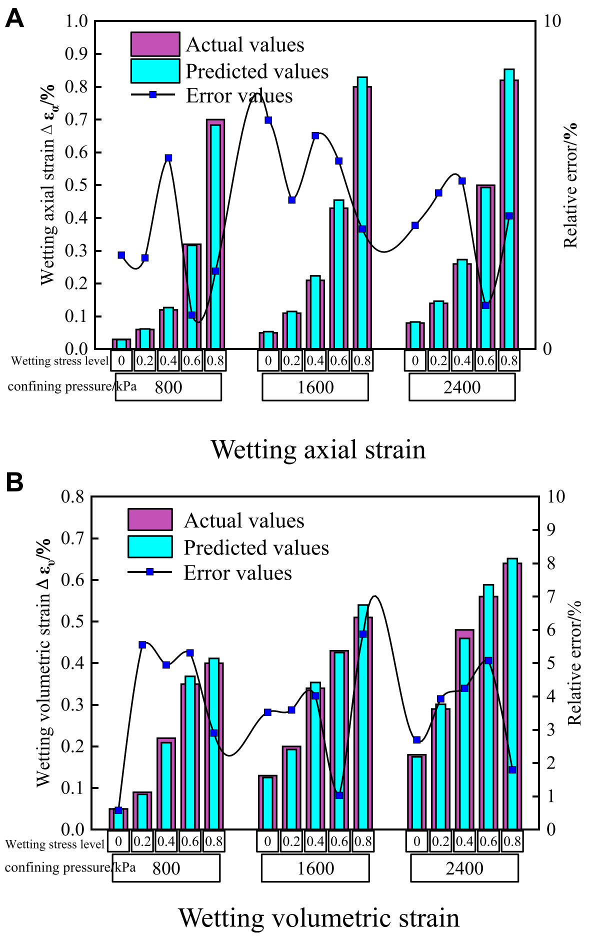

FIGURE 12
Comparison of predicted and measured values of wetting deformation. **(A)** Wetting axial strain **(B)** Wetting volumetric strain.

5 Conclusion

In this research, based on the previous research results of wetting deformation, the model parameters are fitted by triaxial wetting test data, and the wetting deformation of each model is calculated and compared with the test data. The proposed wetting axial strain model and wetting volumetric strain model are verified and analyzed. The P-Z model is improved by using the empirical formula of the wetting model. Based on the P-Z wetting model, the BP neural network is introduced to train the deformation of the wetting test, and the artificial neural network wetting deformation prediction model based on the P-Z model is established. Finally, the following conclusions are drawn.

(1) The experimental data are used to fit the parameters to the wetting model proposed by the previous authors and to calculate the wetting deformation, and the results showed that: The relationship between wetting axial strain and wetting stress level is best fitted by exponential function I (Formula 1); The relationship between the wetting volumetric strain and the wetting stress level is best fitted by the linear function expression of Cheng (Formula 5).

(2) The results of the finite element numerical simulation based on the P-Z wetting model are compared with the results of the triaxial wetting test to verify the accuracy of the P-Z wetting model in simulating the wetting deformation law of coarse-grained materials, indicating that the P-Z model can better reflect the wetting deformation characteristics of coarse-grained materials under complex stress paths, providing a basis for the application of the P-Z model in practical engineering.

(3) In the proposed BP neural network wetting deformation prediction model, the relative error between the predicted and tested values are controlled within 6%, indicating that the prediction model is more reliable and accurate, and can meet the accuracy requirements for wetting deformation prediction.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material further inquiries can be directed to the corresponding author.

Author contributions

HZ: Funding acquisition, Investigation, Content conception, Data analysis and Resource; XL, PH, and YY: Experimental protocol design,Operation, Data processing; XL: Writing, Forming the first draft, and Further analysis. JL, ZD, and LH: Software, Supervision, and Validation; XZ and SW: Reviewed the text and revised the draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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