An ANN-based failure pressure prediction method for buried high-strength pipes with stray current corrosion defect

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Abstract

With continued increasing construction of both electrified facilities and buried high-strength pipelines in China, stray current corrosion defects have become an non-ignorable threat for these pipelines. A comprehensive investigation on a new failure pressure prediction model for high-strength pipes with stray current corrosion defects was conducted in this study. The mechanism of stray current corrosion in steel pipes was firstly elaborated in brief. After that, a parameterized finite element model for stress analysis of pipes with external corrosion defects was programmed by APDL code developed by general software ANSYS. By comparing numerical results with full-scale experimental results, both the numerical model and the failure criteria for pipe burst were proven to be reasonable. Based on the finite element model, parametric analysis was performed using a calculation matrix set by orthogonal testing method to investigate the effects of three main dimensionless factors, that is, ratio of pipe diameter to wall thickness, nondimensional corrosion defect length, and nondimensional corrosion defect depth on pipe's failure pressure. Utilizing the parametric analysis results as database, a multilayer feed-forward artificial neural network (ANN) was developed for failure pressure prediction. By comparison with experimental burst test results and results of previous failure pressure estimation model, the ANN model results were proven to have both high accuracy and efficiency, which could be referenced in residual strength or safety assessment of high-strength pipes with corrosion defects.

KEYWORDS

artificial neural network (ANN), failure pressure prediction, finite element analysis, orthogonal testing method, stray current corrosion defects

1 INTRODUCTION

Buried steel pipelines are recognized as a main choice for transporting natural liquid hydrocarbon fluids (ie, oil and gas) over long distance. In China, there have been more than 120 000 km long buried pipelines in services so far. And in recent decades, high-strength steel pipelines, that is, the X80 steel pipelines, are preferred by pipeline operators for their larger throughput comparing with low- to medium-strength steel pipes. Buried pipelines cross various regions
including both remote countryside and urban areas, which makes them vulnerable to environmental threats. The stray current corrosion in buried steel pipelines induced by adjacent electrified facilities has found to be a new threat for buried steel pipelines in China. Stray current corrosion can lead to corrosion defects in external surfaces of steel pipes in short time, and the thinner pipe wall thickness induced by corrosion will directly increase the von Mises stresses in the corrosion area in pipe until burst failure occurs. Some efforts by a series of researchers have been put on the corrosion mechanism of buried steel pipelines and general steel structure due to stray currents. And some engineering control methods on stray current corrosion have also been proposed.

Some other researchers focused on the failure assessment and residual strength prediction models of steel pipes with corrosion defects. Zhu and Lei derived the failure pressure of corroded steel pipes with considering pipe steel's strain hardening phenomenon. Chen et al. proposed some semi-empirical equations for high-strength pipes with interacted corrosion defects. Ma et al. established a regression-based model for corroded high-strength pipes, which has been proved to be more accurate than the common models recommended by ASME B31G (2012), API 579 (2016), and DNV RP101 (2008). Velazquez et al. conducted probabilistic analysis on failure pressure of corroded pipes using various code-based failure pressure estimation models. Liu et al. utilized a refined numerical model to investigate effects of service loads on the residual strength of oil tube with electrochemical corrosion defects. Terán et al. performed comparative study on the feasibility of various failure pressure estimation methods specified in different guidelines on the pipes with combined corrosion defects. Witek analyzed the failure probability of gas pipelines and the effects of repair activities on them. Zhang established finite element models based on general software ABAQUS for pipes with both single and two corrosion defects. Possible interactions of adjacent corrosion defects on failure pressure were discussed. Shuai conducted the probabilistic analysis of corroded pipes based on the new failure pressure model proposed by Ma. Tian conducted both experimental and numerical studies on failure behavior of corroded or scratched pipes under combined denting and internal pressure loading.

Although a lot of literature is available, less attention is paid on the failure pressure analysis of high-strength pipes with stray current corrosion defects, especially on developing some intelligent failure pressure prediction methods for these defected pipelines. To fill this gap, the mechanism of stray current corrosion in buried steel pipelines was elucidated briefly. After that, a finite element model for failure pressure calculation of high-strength pipe with corrosion defect was established and validated by previous full-scale burst tests. Based on the parameterized numerical model, parametric analysis was performed to study effects of corrosion geometrical parameters on pipe's failure pressure using orthogonal testing method. With database derived from parametric analysis, an artificial neural network (ANN) was adopted for failure pressure prediction, comparisons with the experimental results and previous numerical results show that good agreements were achieved by the ANN model. Thus, the presented study can be directly applied to both failure pressure prediction and safety assessment of high-strength pipes with stray current corrosion. What's more, it also can be referenced in residual strength evaluation of buried steel pipes with other types of corrosion defects.

## 2 STRAY CURRENT CORROSION OF BURIED STEEL PIPES

In recent years, rapid economic development in China leads to a large number of constructions of both electrified facilities and buried high-strength steel pipelines. And investigations show that stray current corrosion defects have been found on buried steel pipelines near electrified facilities, for example, trails, threatening the integrity of pipelines. The No. 2 subway in City Changsha, China, was found to be the main reason for corrosions of one western gas pipeline crossing it. The stray current corrosion is an electrochemical action of electrochemical corrosion essentially. According to the type of interference, the stray current source can be divided into static interference current and dynamic interference current. As shown in Figure 1A, the static interference current in the pipe is usually forcibly imposed by the current system, such as anode beds or other external structures. The shaded pipe in the figure is corroded by stray current from the cathodic protection device, and the arrows point to the directions of stray currents. Most of the dynamic interference currents come from power transmission systems, such as subways, trains, and mining operations, which can be transmitted to a few kilometers away by the adjacent pipe network which has a perfect anticorrosive coating. The buried steel pipelines and structures will be corroded by this kind of stray currents if no measures are taken to eliminate it. Figure 1B shows the stray current caused by an electrified rail, the shaded pipe is corroded by stray currents from the rail, and the arrows point to the directions of stray currents.

The potential difference (PD) will be formed when the stray current flows in the pipe due to the conductivity of buried steel pipe, which can create corrosive batteries: The metal part for the current inflow can be called cathode region, and the metal part for current outflow can be called the anode region of the corrosion battery.

The anodic and cathodic reactions will occur in the anode and cathode regions, respectively. According to the different environment of the buried steel pipeline, the cathode reaction has different reaction forms, but the anode
reaction is all the same, as shown in Table 1. Therefore, a large number of OH$^-$ are accumulated in cathode region, and a great deal of Fe$^{2+}$ gather in anode region. Due to diffusion, Fe$^{2+}$ and OH$^-$ are combined into corrosion products Fe(OH)$_2$ in soil, and they will be oxidized to rust components like Fe$_2$O$_3$·2H$_2$O and Fe$_3$O$_4$, which result in pipe corrosion.

If the stray current intensity in the pipe is known, the quantity of metal loss caused by stray current corrosion can be estimated as follows:

$$M = KitiT$$

(1)

where $M$ is the mass of the metal loss; $K$ is the electrochemical equivalent of metal material of the pipe, $K = M'/nF$; $i$ is the intensity of the current flows from the anode region; $T$ is corrosion time; $M'$ is molar mass of the metal; $n$ is the number of valence electrons lost in the process of metal oxidation; and $F$ is the Faraday constant.

Therefore, the mass of metal loss caused by stray current corrosion is proportional to the magnitude of stray current. But the actual corrosion quantity is quite different from the one calculated by Equation 1, which is affected by soil environment, biological environment, electric erosion coefficient, and other factors.

Based on the mass of metal loss, corrosion defect parameters can be estimated and combined with the numerical model for stress calculation of pipes with corrosion defects. Failure pressure and residual strength (life) of pipe under the effect of stray current corrosion can be derived.

### 3 | STRENGTH ANALYSIS MODEL FOR PIPELINES WITH CORROSION DEFECTS

#### 3.1 | High-strength X80 line pipe steel

X80 line pipe steel is a typical high-strength steel widely used in oil and gas industry. As a typical high-strength alloy steel, it has complex chemical components to enhance its mechanical properties, as shown in Table 2.

The mechanical properties for X80 line pipe specified by the API 5L standard are also listed in Table 3. And for the presented study, the special X80 steel provided by Ma et al.
was utilized for the numerical analysis. Ma used the well-recognized Ramberg-Osgood model (Equation 2) to regress the true stress-strain curve of the X80 steel Figure 2. The yield offset parameter $\alpha$ and the strain hardening exponent $r$ derived were 1.043 and 11.19, respectively.

$$
\varepsilon = \frac{\sigma}{E} + \alpha \frac{\sigma}{E} \left( \frac{\sigma}{\sigma_0} \right)^{r-1}
$$

(2)

### 3.2 | Finite element model

Stray current–induced corrosion defects are located on the external surface of buried steel pipe. As a volumetric defect, corrosion defects have three main geometrical parameters, as shown in Figure 3. The corrosion defect length $L$ represents the total length of the defect in the axial direction of pipe. The corrosion defect depth $d$ represents the height of the corrosion bottom to the original pipe external surface. The corrosion defect width $W$ represents the circumferential length of the defect in the circumferential direction of pipe.

In this study, the general finite element software package ANSYS was utilized to establish the numerical model (ANSYS Release 12.1 Documentation 2009). For both geometrical and loading conditions of the model is symmetric, a quarter model is sufficient for numerical investigation, as shown in Figure 4. Length of the established one quarter pipe is five times of the pipe diameter in order to avoid the boundary effects on calculated stress results. The 3D 20-Node homogeneous solid element was adopted for pipe meshing, with a very fine mesh in the corrosion area and a relatively coarse mesh for the pipe segments away from the corrosion defect. A gradual transition in pipe axial direction was conducted to realize this. For the radial direction of pipe, four layers of equivalent thickness solid elements were set for the accurate calculation of stress results. Suitable boundary conditions were applied on the three surfaces of the one quarter model, that is, Surface A, Surface B, and Surface C. UZ of Surface B and UX of Surface A are restrained to simulate the symmetric boundary conditions of the two surfaces. While UX of Surface C is also restrained to simulate the plane strain state of buried pipelines induced by soil constraints. At the same time, UY of the line at the bottom of the pipe has been also restrained to prevent the pipe free to move. Only one step is needed for this numerical analysis, in which the internal pressure is applied to the inner surfaces of the pipe. But it is worthy to mention that, when the von Mises stress in pipe is close to the ultimate strength of pipe steel, the pipe stiffness decreases largely which is easy to induce convergence problem. Thus, the modified Riks algorithm, which is capable of addressing this kind of unstable collapse behavior, is adopted in solving this numerical model (ANSYS Release 12.1 Documentation 2009). It also should be noticed that the numerical model was completely programmed by the APDL language, a code provided by ANSYS for parameterized programming and secondary development, which makes the parametric analysis in this study can be conducted readily.

### 3.3 | Failure criteria for high-strength pipe burst rupture

Previous researches show that pipe burst failure behavior induced by internal pressure is a material plastic collapse behavior. Specifically for pipes with corrosion defects, pipe failure occurs when the von Mises stress in the pipe reaches the yield stress.
critical section of corrosion area reaches the flow stress of pipe material. Ma summarized four common flow stress values used for line pipe steels, the ultimate strength, 90% of the ultimate strength, 80% of the ultimate strength and the average value of the ultimate strength and yield strength. By comparing with some collected experimental results, Ma concluded that, for X80 high-strength steel, the suitable flow stress for failure recognition is the ultimate strength.13

In this section, experimental results summarized by Ma were also adopted to validate the accuracy of our established numerical model and the failure criteria presented by Ma. The experimental parameters of six groups of full-scale burst tests are listed in Table 4.

The failure procedure of the case EXP No. 3 is analyzed here as an example. Figure 5 illustrates the trends of the von Mises stresses at three different points in the critical section in the center of the corrosion area. Results show that initially the von Mises stress at the external point and the von Mises stress at the inner point are the largest and smallest, respectively, which are in agreement with the elastic theory results of thick-walled cylinder structures subjected to internal pressure load. But when the von Mises stress at the external point reached the yield strength of pipe steel, it remains constant with increase of internal pressure, until the von Mises stresses in the entire section reached the yield strength. During this stage, the stiffness of the external point has become soften, it has much less bearing capacity comparing with the inner points in this section. Thus, von Mises stress of the inner points increases, as they are bearing the huge hoop stress induced by internal pressure. But once the entire section becomes plastic, the von Mises stresses in the whole section become almost the same. In this final plastic deformation stage, the pipe can be considered as rupture, once the von Mises stress reaches the ultimate strength of pipe material. As shown in Figure 5, the calculated failure pressure is 23.14 MPa for EXP No. 3, which is almost the same with the experimental result 23.3 MPa. Figure 5 also shows the unloading phenomenon of the internal pressure after the von Mises stresses reached the yield strength. Actually, this phenomenon has no actual physical meaning, it is derived by the iterative algorithm of the modified Riks method to ensure the convergence of the calculation. The burst moment of EXP No. 3 is also plotted in Figure 6. It shows that the corrosion center has totally become plastic at the failure point.

The failure pressure results derived by the presented finite element model for the six groups of full-scale burst experiments listed in Table 4 were further compared with both
the experimental results and the numerical results calculated by Ma using a rigorous finite element model established by ABAQUS as shown in Figure 7. It is obvious that these three sets of results are all in good agreement for all six groups of experiments. Thus, the presented model can be used for failure pressure calculation for pipes with corrosion defects.

4 | PARAMETRIC ANALYSIS USING ORTHOGONAL TESTING METHOD

Most of the available researches on failure pressure prediction models for steel pipes with corrosion defects were conducted by regression analysis based on a large amount of numerical and (or) experimental results.12,13 The database for this kind of analysis is large, because pairwise testing is commonly adopted in these parametric analyses.29 For instance, in Ma’s study, more than 200 cases were used.13

For our presented study, failure pressure of corroded X80 pipes is influenced by five main parameters, that is, the pipe diameter $D$, the pipe wall thickness $t$, the corrosion defect length $L$, the corrosion defect depth $d$, and the corrosion defect width $W$. Using the Bucking-Pi theorem, these five parameters can be reduced to four independent nondimensional parameters, that is, ratio of pipe diameter to wall thickness $D/t$, nondimensional corrosion defect depth $d/t$, nondimensional defect length $L/\sqrt{Dt}$, and nondimensional corrosion defect width $W/\pi D$. As Ma found that the corrosion defect width has tiny effects on failure pressure of corroded high-strength steel pipes, only the effects of $D/t$, $d/t$, and $L/\sqrt{Dt}$ on X80 pipe’s pressure need to be considered.13

### TABLE 4 Experimental parameters for the six groups of full-scale tests for X80 steel pipes

| EXP No. | Diameter $D$ (mm) | Wall thickness $t$ (mm) | Corrosion defect length $L$ (mm) | Corrosion defect depth $d$ (mm) | Failure pressure $P_{\text{lim}}$ (MPa) |
|---------|------------------|------------------------|-------------------------------|-------------------------------|--------------------------------------|
| 1       | 1219             | 19.89                  | 606                           | 15.4                          | 7.6                                  |
| 2       | 1219             | 19.89                  | 606                           | 7.4                           | 17.7                                 |
| 3       | 1219             | 19.89                  | 608                           | 1.8                           | 23.3                                 |
| 4       | 1219             | 13.79                  | 588                           | 10.8                          | 4.7                                  |
| 5       | 1219             | 13.79                  | 589                           | 5.4                           | 12                                   |
| 6       | 1219             | 13.79                  | 586                           | 1.5                           | 16.1                                 |

![FIGURE 5 Trends of the von Mises stress of the three points in the thickness direction in center of the corrosion defect of EXP 3](image1)

![FIGURE 6 Burst failure moment for the case EXP No. 3](image2)

![FIGURE 7 Comparison results of the burst pressure for the 6 groups of experiments](image3)
4.1 Ranges of nondimensional parameters

In this section, ranges of the mentioned three nondimensional parameters are concluded. The ratio of the pipe diameter to pipe wall thickness can be derived according to Equation 3.

\[
\frac{PD}{2t} = [f] \sigma_s
\]

where \([f]\) is the safety factor, which can be 0.4, 0.5, 0.6, 0.72, and 0.8. This value depends on the risk level of the region where pipelines located, according to ASME B31.8.

The length of corrosion defects has various effects on failure pressure of corroded X80 pipeline for different magnitudes. If \(L/\sqrt{Dt}\) is less than 5, the corrosion defect is more like a pit (ellipsoidal) corrosion (Figure 8A), \(P_{lim}\) decreases obviously with \(L/\sqrt{Dt}\) increases. But if \(L/\sqrt{Dt}\) is larger than 5, the corrosion defect is more like a long and narrow corrosion (Figure 8B), \(P_{lim}\) decreases tinnily with \(L/\sqrt{Dt}\) increases. If \(L/\sqrt{Dt}\) is larger than 15, it has no effect on the failure pressure. Thus, corrosion defects are classified into two kinds of defects to conduct the parametric analysis, and ranges of all the three nondimensional parameters for the two shapes of corrosion defects can be summarized in Table 5.

### Table 5

| Ratio of pipe diameter to wall thickness \(D/t\) | Nondimensional defect depth \(d/t\) | Nondimensional defect length \(L/\sqrt{Dt}\) |
|---------------------------------------------|-----------------------------------|-------------------------------------------|
| Pit (ellipsoidal) corrosion | 36.67, 45.83, 55.00, 66.00, 73.33, | 0.2, 0.3, 0.4, 0.5, 0.6 | 1, 2, 3, 4, 5 |
| Long and narrow corrosion | 36.67, 45.83, 55.00, 66.00, 73.33, | 0.2, 0.3, 0.4, 0.5, 0.6 | 7, 9, 11, 13, 15 |

4.2 Setup of calculation matrix for parametric analysis

Orthogonal testing method is a high efficient method for regression testing, system testing and performance testing and so on. It has much smaller database for a same problem using the common pairwise testing. But it should be mentioned that, for the orthogonal property of the testing arrays, all tested cases according to this method are balanced which makes it straightforward to isolate defects and assess performance. It is especially suitable for the problems that the input parameter kinds are relatively small, such the failure pressure prediction problem in the presented study.

Thus, two three-factor five-level orthogonal test tables were listed in this section with the nondimensional parameter listed in Table 5 for the two kinds of corrosion defects. Corresponding finite element models were established by ANSYS using the parameterized programs coded by APDL language. The failure pressures for all the cases of pit corrosion defects and long and narrow corrosion defects are calculated and listed in the last row of Table 6 and Table 7, respectively.

5 FAILURE PRESSURE PREDICTING MODEL BASED ON ARTIFICIAL NEURAL NETWORK

An artificial neural network (ANN) is a group of artificial neurons connected together by synapses, which transmit signals between each connected ones. Typically, one ANN organizes the neurons in different layers, which perform different transformations on their inputs from their upstream layers to their outputs in their downstream layers. The output of each neuron can be calculated by nonlinear functions of the sum of all its input. There are various functions can be selected to build a network. And different weights can be set to the neurons and synapse, which can change their effects on their downstream. The ANN was developed to simulate the human brains to solve sophisticated problems, which can be trained by samples. During the training process, according to the errors derived between the outputs and expected results, weights of the neurons and synapses can be modified to correct the outputs.
The multilayer feed-forward neural network is the one widely used ANN in many research areas which can handle the complicated nonlinear relationships between various system inputs and outputs. Xu et al.31 used the ANN for limit pressure prediction of subsea pipes with defects. Shokouhi et al.32 predicted the bending strain of HDPE pipes under tectonic active faults with a GA improved ANN. Thus, an ANN was also adopted here to establish this failure pressure prediction model.

### 5.1 Development of artificial neural network for failure pressure of corroded X80 steel pipelines

A multilayer feed-forward neural network with backpropagation learning algorithm was developed in this study for failure pressure prediction of X80 pipe with corrosion defects. According to the parametric analysis in Section 3, three inputs of the ANN were the ratio of pipe diameter to wall thickness, nondimensional corrosion defect length, and nondimensional corrosion defect depth. The output of the ANN was the failure pressure of pipe.

The artificial neural network toolbox developed by MATLAB was utilized to build the ANN. The transfer function between the input layer and the hidden layer was set to be “logsig” (Figure 9A), while the transfer functions between the hidden layer and the output layer were set be “purelin” (Figure 9B). It is worthy to mention that the Levenberg-Marquardt method was adopted in backpropagation learning algorithm for adjusting the weights of the synapses.

Six kinds of artificial neural network structure with various number of neurons and number of hidden layers were compared here to derive a suitable network for failure pressure prediction. Results of the mean squared error obtained by the networks are listed in Table 8, which shows that one hidden layer with 7 neurons is the best choice for the presented problem. Structure of the ANN with one hidden layer with seven neurons is illustrated in Figure 10.

### Table 6 Calculation matrix for failure pressures of X80 pipe with pit (ellipsoidal) corrosion defect

| Ratio of pipe diameter to wall thickness $D/t$ | Nondimensional corrosion defect depth $d/t$ | Nondimensional corrosion defect length $L/\sqrt{Dt}$ | Failure pressure $P_{\text{lim}}$ (MPa) |
|---------------------------------------------|---------------------------------------------|---------------------------------------------|-------------------------------------|
| No. 1 36.67                                 | 0.2                                         | 1                                           | 37.61                               |
| No. 2 36.67                                 | 0.3                                         | 2                                           | 33.64                               |
| No. 3 36.67                                 | 0.4                                         | 3                                           | 29.22                               |
| No. 4 36.67                                 | 0.5                                         | 4                                           | 24.67                               |
| No. 5 36.67                                 | 0.6                                         | 5                                           | 20.10                               |
| No. 6 45.83                                 | 0.2                                         | 2                                           | 28.72                               |
| No. 7 45.83                                 | 0.3                                         | 3                                           | 25.64                               |
| No. 8 45.83                                 | 0.4                                         | 4                                           | 22.33                               |
| No. 9 45.83                                 | 0.5                                         | 5                                           | 18.95                               |
| No. 10 45.83                                | 0.6                                         | 1                                           | 24.41                               |
| No. 11 55                                   | 0.2                                         | 3                                           | 23.22                               |
| No. 12 55                                   | 0.3                                         | 4                                           | 20.70                               |
| No. 13 55                                   | 0.4                                         | 5                                           | 18.07                               |
| No. 14 55                                   | 0.5                                         | 1                                           | 21.93                               |
| No. 15 55                                   | 0.6                                         | 2                                           | 17.26                               |
| No. 16 66                                   | 0.2                                         | 4                                           | 18.98                               |
| No. 17 66                                   | 0.3                                         | 5                                           | 16.91                               |
| No. 18 66                                   | 0.4                                         | 1                                           | 19.27                               |
| No. 19 66                                   | 0.5                                         | 2                                           | 16.00                               |
| No. 20 66                                   | 0.6                                         | 3                                           | 12.78                               |
| No. 21 73.33                                | 0.2                                         | 5                                           | 16.88                               |
| No. 22 73.33                                | 0.3                                         | 1                                           | 18.10                               |
| No. 23 73.33                                | 0.4                                         | 2                                           | 15.66                               |
| No. 24 73.33                                | 0.5                                         | 3                                           | 13.13                               |
| No. 25 73.33                                | 0.6                                         | 4                                           | 10.61                               |
TABLE 7  Calculation matrix for failure pressure of X80 pipe with long and narrow corrosion defect

| Ratio of pipe diameter to wall thickness $D/t$ | Nondimensional corrosion defect depth $d/t$ | Nondimensional corrosion defect length $L/\sqrt{Dt}$ | Failure pressure $P_{lim}$ (MPa) |
|---------------------------------------------|------------------------------------------|-----------------------------------------------|---------------------------------|
| No. 1 36.67                                 | 0.2                                      | 7                                             | 33.34                           |
| No. 2 36.67                                 | 0.3                                      | 9                                             | 29.58                           |
| No. 3 36.67                                 | 0.4                                      | 11                                            | 25.84                           |
| No. 4 36.67                                 | 0.5                                      | 13                                            | 22.09                           |
| No. 5 36.67                                 | 0.6                                      | 15                                            | 18.28                           |
| No. 6 45.83                                 | 0.2                                      | 9                                             | 26.54                           |
| No. 7 45.83                                 | 0.3                                      | 11                                            | 23.59                           |
| No. 8 45.83                                 | 0.4                                      | 13                                            | 20.64                           |
| No. 9 45.83                                 | 0.5                                      | 15                                            | 17.66                           |
| No. 10 45.83                                | 0.6                                      | 7                                             | 15.18                           |
| No. 11 55                                   | 0.2                                      | 11                                            | 22.08                           |
| No. 12 55                                   | 0.3                                      | 13                                            | 19.63                           |
| No. 13 55                                   | 0.4                                      | 15                                            | 17.18                           |
| No. 14 55                                   | 0.5                                      | 7                                             | 15.13                           |
| No. 15 55                                   | 0.6                                      | 9                                             | 12.36                           |
| No. 16 66                                   | 0.2                                      | 13                                            | 18.38                           |
| No. 17 66                                   | 0.3                                      | 15                                            | 16.35                           |
| No. 18 66                                   | 0.4                                      | 7                                             | 14.60                           |
| No. 19 66                                   | 0.5                                      | 9                                             | 12.39                           |
| No. 20 66                                   | 0.6                                      | 11                                            | 10.21                           |
| No. 21 73.33                                | 0.2                                      | 15                                            | 16.54                           |
| No. 22 73.33                                | 0.3                                      | 7                                             | 14.91                           |
| No. 23 73.33                                | 0.4                                      | 9                                             | 12.98                           |
| No. 24 73.33                                | 0.5                                      | 11                                            | 11.08                           |
| No. 25 73.33                                | 0.6                                      | 13                                            | 9.15                            |

Based on the optimized network structures, two ANNs were developed for pipe with the two kinds of corrosion defects separately. In each ANN, 25 burst pressure results were classified into 3 sets for net training. The percentages of the training data set, validation data set, and test data set were chosen to be 76%, 12%, and 12%, respectively. Figure 11

FIGURE 9  Transfer functions in the ANN
illustrates the results of the trained ANN for X80 pipe with pit (ellipsoidal) corrosion defect, which shows good agreement for all the 25 cases.

5.2 Model validation

To further validate the accuracy of the presented model, six experimental results listed in Table 4 were adopted here for the comparison analysis. What's more, an accurate regression model for failure pressure of corroded high-strength steel pipe presented by Ma was also considered here for comparison, for it has more precise results comparing with the formulas provided by ASME B31G (2009), API 579 (2009), and DNV RP101 (2004).

Figure 12 shows the comparison results, which can be readily found that insignificant deviation existed between the experimental results and the predicted results through the proposed ANN model and Ma's regression model. The maximum relative error for the ANN was observed to be 16% (EXP No. 1). Thus, this established model is capable to perform failure pressure prediction of high-strength X80 pipes with stray current corrosion defects. What's more, the database of our presented method is less than half of the database Ma used for regression analysis, which reflects that this proposed method has much higher efficiency comparing with common regression analysis method.

6 CONCLUSIONS

A comprehensive investigation on a new failure pressure prediction method for high-strength pipes with stray current corrosion defects has been performed throughout this paper, for stray current corrosion has become one nonignorable threat of buried steel pipeline, according to the investigations in China. The mechanism of stray current corrosion in steel pipes was briefly introduced first. And a novel failure pressure prediction model for high-strength steel pipes was proposed as a reference for the assessment of these corroded pipelines, based on nonlinear finite element analysis and artificial neural network model. Some remarkable conclusions can be drawn as follows:

1. At the burst failure moment of corroded pipes, the failure section in corroded area becomes fully plastic. The pipe can be considered to occur burst rupture failure, once the von Mises stress in the failure section reaches the ultimate strength of pipe material.

| Case No. | Number of neurons | Number of hidden layers | MSE       |
|---------|-------------------|-------------------------|-----------|
| No. 1   | 5                 | 1                       | 2.07 × 10⁻⁴ |
| No. 2   | 5                 | 2                       | 2.73 × 10⁻⁴ |
| No. 3   | 7                 | 1                       | 1.76 × 10⁻⁴ |
| No. 4   | 7                 | 2                       | 2.88 × 10⁻⁴ |
| No. 5   | 10                | 1                       | 6.19 × 10⁻⁴ |
| No. 6   | 10                | 2                       | 1.32 × 10⁻³ |

**FIGURE 10** ANN structure for failure pressure prediction
2. Considering the ultimate strength as the failure criteria for high-strength pipes with corrosion defect was verified to be reasonable for numerical analysis by comparing with experimental and previous numerical results.

3. The three-layer feed-forward neural network model can predict failure pressure of high-strength pipes with stray current corrosion defect accurately through a relative small database realized by the orthogonal testing method.

4. Comparing with the accurate regression model presented by Ma for high-strength pipe with corrosion defect, the presented model has similar accuracy and higher efficiency, which can give a good reference for residual strength prediction of pipes with corrosion defects.

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