Prediction of Submarine Pipeline Corrosion Based on the Improved Grey Prediction Model

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Abstract. To predict the degree of corrosion and remaining life of submarine pipelines more accurately, and to prevent pipeline leakage accidents caused by the pipeline corrosion in advance, an improved grey model that applies appropriate translation and sine transformation to the original series was established. And the initial value of the time-corresponding function was optimized when the model was solved. Compared with the two grey models mentioned in the paper, the accuracy of the improved grey model has been improved, and the stability of the model was better. The result shows that the prediction result of the improved grey model is closer to the measured value.

1. Introduction
Corrosion is one of the important factors, which damage the integrity of the pipeline. Leakage accidents caused by pipeline corrosion have occurred both at home and abroad. In 2013, the Donghuang pipeline in Qingdao caused an explosion accident due to corrosion[1]. From 1986 to 2016, CNOOC had 51 submarine pipeline accidents, of which 37% were caused by corrosion[2]. From 1988 to 2008, gas pipeline accidents by corrosion in North American accounted for 18%[3]. Therefore, it is necessary to predict and evaluate the corrosion degree of pipelines.

Yan Li et al.[4] proposed the use of extreme value statistics to predict the size of pipeline pitting corrosion, and then evaluated the remaining strength of the pipeline. Seo et al.[5] proposed the use of time-varying corrosion model failure probability and failure consequences to predict the degree of pipeline rupture. Li et al.[6] proposed a combination of limit state equations and Monte Carlo methods to establish a submarine oil and gas pipeline corrosion failure risk warning model. In addition to the above three methods, predictive methods can also be used to evaluate the corrosion degree of pipelines. For example, the gray model has long been applied in the oil and gas storage and operation industry[7]. Because most of the original series cannot be used directly in the conventional gray model, Cui[8] proposed that the original series should be appropriately transformed when using the conventional gray model to meet the smoothness, level ratio compression, unevenness and reducibility.

There are many ways to transform the original sequence, such as trigonometric function method[9,10], logarithmic function method[11], power function transformation method[12,13], optimized initial value method[14], and related results have also been applied in practice. Wang et al.[15] proposed the use of gray Markov model to predict pipeline corrosion. In order to further improve the accuracy of gray Markov model for predicting pipeline corrosion, Zhang et al.[14] proposed the use of
optimized initial values to solve the time response function. There are also combined applications. Li et al. [16] proposed the use of gray prediction and neural network combined models to predict oil and gas pipeline corrosion.

The above gray models all achieve the effect of basically overlapping the predicted values and actual measured values, and the accuracy is higher than that of the conventional gray models. However, none of the above gray models combine the information of effectively transforming the original number sequence and fully utilizing the original number sequence. In order to further improve the prediction accuracy of gas pipeline corrosion, this paper uses an improved power function translation and transformation method to establish a gray model.

2. Conventional grey model

2.1. Built a conventional grey model

To establish a conventional grey model. Give a sequence.

\[ X^{(0)}(k) = \{x^{(0)}(1), x^{(0)}(2), \ldots x^{(0)}(n)\} \]  \hspace{1cm} (1)

Claim \(X(0)(k) > 0\), and \(k = \{1, 2, \ldots, n\}\).

Step 1: Processed preliminary for the sequence. Accumulate the sequence \(X^{(0)}\) based on once accumulation to get a new sequence \(X^{(1)}\)

\[ X^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i), k = \{1, 2, 3, \ldots, n\} \]  \hspace{1cm} (2)

Then use the new sequence \(X^{(1)}(k) = \{x^{(1)}(1), x^{(1)}(2), \ldots, x^{(1)}(n)\}\) to establish a grey model.

Step 2: Established the whitening equation of the grey model. For \(X^{(1)}(k)\), it was regard as \(X^{(1)} = X^{(1)}(t)\) with a continuous function of time,

\[ \frac{dX^{(1)}}{dt} + aX^{(1)} = b \]  \hspace{1cm} (3)

In the formula: \(a\) is the development coefficient of the grey model; \(b\) is the grey action coefficient of the grey model. Let the parameter list:

\[ z^{(1)}(k) = \frac{1}{2}[x^{(1)}(k) + x^{(1)}(k-1)], k = \{2, 3, \ldots, n\} \]

\[ B = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z^{(1)}(n) & 1 \end{bmatrix} \quad \text{and} \quad Y = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{bmatrix} \]

In the formula: \(z^{(1)}(k)\) is the mean value of any two adjacent items of \(X^{(1)}(k)\).

Step 3: Solved the whitening equation. Rewrite (3) from the parameter column to

\[ \begin{bmatrix} a \\ b \end{bmatrix} = (B^T B)^{-1} B^T Y \]

And get the time response function of the conventional grey model,

\[ x^{(1)}(k) = [x^{(0)}(1) - \frac{b}{a}]e^{-a(k-1)} + \frac{b}{a}, k = \{2, \ldots, n\} \]  \hspace{1cm} (4)

In the formula: \(x^{(1)}(k)\) is a discrete predictive sequence, and \(x^{(1)}(1) = x^{(0)}(1)\).

Step 4: Restored the predicted series. It can be obtained with a cumulative subtraction,

\[ x^{(0)}(k) = x^{(1)}(k) - x^{(1)}(k-1), k = \{2, \ldots, n\} \]  \hspace{1cm} (5)
In the formula: $\hat{x}^{(0)}(1) = x^{(0)}(1)$

2.2. Optimized the initial value of the forecast

When solving the whitening equation of the conventional grey model, the elements in the original sequence are not fully utilized, but only the first element is used to solve the time response function, such as $x^{(0)}(1)$ in formula (4). In fact, the new sequence $X^{(1)}(k)$ after one accumulation contains the information of each element in the original sequence $X^{(0)}(k)$, so the $x^{(0)}(1)$ replaced with $x^{(1)}(n)$. After optimized the predictive initial value, all the information in the original series can be fully utilized when solving the time response function. And get a new time response function,

$$\hat{x}^{(1)}(k) = \left[ x^{(1)}(n) - \frac{b}{a} \right] e^{-a(k-n)} + \frac{b}{a}, k = \{2, \cdots, n\}$$

(6)

3. Improved grey model

The conventional gray model requires the original series with appropriate the smoothness, the series ratio, the accidented and the reducibility, otherwise the prediction result does not conform to the actual situation. The original number sequence under different application backgrounds, however, has different characteristics, which may not all meet these conditions. Therefore, before established the gray model, it is necessary to appropriately transform the original sequence to satisfy the conditions. The sequence transformed by the right translation and the sine function transform can satisfy this condition. The model was built as follows.

3.1. The sequence was translated by power function sequence

Step 1: Translated the original series. The purpose is to make the original sequence better meet the requirements of the conventional gray model.

$$x^{(0)}(k) = \frac{\left(100.05 \times x^{(0)}(k)\right)^{1/1.3408786}}{242.18}$$

(7)

The original number sequence after right translation is more adaptable on the conventional gray model.

3.2. The sequence was transformed by sine function

Step 2: Transformed the original number sequence after translation.

$$y^{(0)}(k) = f(x^{(0)}(k)) = \sin(2 \times x^{(0)}(k))$$

(8)

Then got the new sequence $Y^{(0)}(k)$,

$$Y^{(0)}(k) = \{y^{(0)}(1), y^{(0)}(2), \cdots y^{(0)}(n)\}$$

(9)

3.3. Restored the forecast sequence

Step 6: Restored the forecast sequence,

(1) First, $\hat{y}^{(1)}(k)$ performs a cumulative subtraction to restore the predicted value $\hat{y}^{(0)}(k)$,

$$\hat{y}^{(0)}(k) = \hat{y}^{(1)}(k) - \hat{y}^{(1)}(k-1), k = \{2, \cdots, n\}$$

(10)

In the formula: $\hat{y}^{(0)}(1) = y^{(0)}(1)$.

(2) Then substituted into the corresponding transformation and translation functions to restore the predicted sequence,
4. Case application and analysis

Take [14] as an example. Take the test section of a submarine pipeline as an example. The sea area has a density of 1025 kg/m$^3$ and a sea depth of 750 m, and the pipe material is API 5L X52, and the pipe outer diameter is 0.4 m, the pipe wall thickness is 10 mm, and the material density is 7850 kg/m$^3$. The yield strength is 360 MPa. The operating pressure is 1.17 MPa in flowing water, and the operating pressure is 7.6 MPa in static water. Over time, corrosion pits can be seen in individual locations of submarine pipelines. Used underwater thickness gauges to detect corrosion pits in the pipeline, every other year, with 10 corrosion depth inspections at one of the inspective points. The value is the original data for experimental analysis (Table 1). It can be seen from Table 1 that the maximum corrosion depth of the pipe wall is increasing gradually. Therefore, it is necessary to predict the degree of corrosion of the pipeline.

Table 1. External impact corrosion value of a submarine pipeline.

| Number | Corrosion depth /mm | Number | Corrosion depth /mm |
|--------|---------------------|--------|---------------------|
| 1      | 0.90                | 6      | 1.95                |
| 2      | 1.05                | 7      | 2.53                |
| 3      | 1.23                | 8      | 3.19                |
| 4      | 1.57                | 9      | 4.01                |
| 5      | 1.78                | 10     | 4.94                |

4.1. Compared of prediction results of different grey prediction methods

The measured values was substituted into the time response functions of the conventional gray model, the model of [14] and the improved gray model. The original measured corrosion value of the submarine pipeline and the predicted corrosion value table of different gray prediction methods can be obtained (Table 2).

Table 2. The original measured value of external impact corrosion of a submarine pipeline and the corrosion prediction value of different gray prediction methods.

| Number | Measured value /mm | Predictive value /mm | Relative error /% |
|--------|--------------------|----------------------|-------------------|
|        |                    | Conventional gray model | Model of [14] | Improved grey model |
| 1      | 0.90               | 0.90                 | 0.00              |
| 2      | 1.05               | 0.93                 | 11.10             |
| 3      | 1.23               | 1.14                 | 11.10             |
| 4      | 1.57               | 1.40                 | 10.70             |
| 5      | 1.78               | 1.72                 | 10.70             |
| 6      | 1.95               | 2.10                 | 7.90              |
| 7      | 2.53               | 2.58                 | 7.90              |
| 8      | 3.19               | 3.16                 | 7.90              |
| 9      | 4.01               | 3.87                 | 7.90              |
| 10     | 4.94               | 4.74                 | 7.90              |
| Average relative error /% | 5.06 | 3.77 | 2.61 |

4.2. Analysis and discussion

At the same time, the curves of predicted corrosion depth and measured values of different gray prediction methods were obtained (Figure 1).

It can be seen from Table 2 and Figure 1 that the trends of the predicted values of the three prediction models are basically the same as the measured values. In the conventional grey model, the predicted values deviate too much from the measured values, except that the predicted values in the 1st, 7th, and 8th years are basically similar to the measured values. Compared with the conventional grey model, the
predicted value of the prediction model of [14] is still close to the measured value, except that the predicted values in the 3rd, 4th, 6th and 7th years. The predicted values of the improved grey model in the 4th, 6th, 7th and 9th years deviate from the measured values, and the predicted values at other time points are similar to the measured values.

Figure.1 The curve of corrosion depth prediction value and actual measurement value in different gray prediction methods.

By comparing the relative error value curves of different models (Figure 2), and it can be seen that the conventional grey model fluctuates 4 times, but the model of [14] and the improved grey model fluctuate 3 times. The overall fluctuation range of the conventional grey model is largest, especially the last fluctuation, makes the overall forecast trend more deviate from the measured value, and the average relative error value of the model is also larger. Compared with the improved grey model, the overall fluctuation range and average relative error of the model of [14] are also larger. For the improved grey model, the fluctuation range and the overall average relative error value in each serial point are smaller than the other two models.

Figure.2 Relative error curve of different models.

In summary, among the three models mentioned in this article, the conventional grey model has the worst stability, followed the model of [14], and the improved grey model is the best. Therefore, it can be seen that the improved grey model established under this application background is more suitable.

4.3. Predicted the remaining strength of the pipeline

According to the current national standard SY/T6151-2009, that is, Steel Pipe Corrosion Damage Evaluation Method (Table 3), and the corrosion damage degree of the pipe is divided into three levels: immediate repair, deadline repair and monitoring use.
Table.3 Classification of corrosion damage assessment category of pipe.

| Category | Repair | Evaluation and conclusion |
|----------|--------|---------------------------|
| 1 | Fix now | The degree of corrosion is very serious and should be repaired immediately |
| 2 | Fix deadline | The degree of corrosion is serious, and a repair plan should be developed or reduced to safe working pressure. |
| 3 | Monitoring | The degree of corrosion is not serious, and it can continue to operate normally, but for monitoring and use, if there is a large additional pressure on the pipe body, it should be considered separately |

According to the improved grey model, the corrosion depth value after two years is predicted. At the same time, the corrosion depth value curve (Figure 3) and the predicted corrosion depth value table (Table 4) by the improved grey model predicts were gotten.

![Improved grey model](image)

Figure.3 The improved gray model predicts the corrosion depth value curve after two years.

Table.4 The predicted corrosion depth value and related repair suggestions for a submarine pipeline after two years.

| Number | Measured value/mm | Improved grey model/mm | Corrosion damage category | Repair suggestions |
|--------|-------------------|------------------------|---------------------------|--------------------|
| 1      | 0.90              | 0.90                   | 3                         | Monitoring use     |
| 2      | 1.05              | 1.04                   | 2                         | -                  |
| 3      | 1.23              | 1.21                   | 2                         | -                  |
| 4      | 1.57              | 1.46                   | 2                         | -                  |
| 5      | 1.78              | 1.77                   | 2                         | -                  |
| 6      | 1.95              | 2.14                   | 2                         | -                  |
| 7      | 2.53              | 2.61                   | 2                         | -                  |
| 8      | 3.19              | 3.19                   | 2                         | -                  |
| 9      | 4.01              | 3.92                   | 2                         | -                  |
| 10     | 4.94              | 4.88                   | 2                         | -                  |
| 11     | –                 | 6.18                   | 2                         | -                  |
| 12     | –                 | 8.15                   | 1                         | Fix now            |

Notes: “-“Indicates that the repaired suggestions are given.

According to the calculation method of the impact of the circumferential corrosion scale in the national standard SY/T6151-2009, when the relative depth of the pipeline corrosion pit is between 10% and 80%, it is necessary to know the specific length of the pipeline and the maximum longitudinal projection length of the corrosion area to give specific repair suggestions, so the specific repair suggestions for the 2nd to 11th are not given in this article.

However, according to Table 4, without any intervention, the predicted corrosion depth of the pipeline will reach 8.08 mm in the 12th year after the start of monitoring. At this time, the relative depth of the corrosion pit has exceeded 80%, that is, it is in the first category of corrosion damage. At this time, the corrosion of the pipeline is very serious and needs to be repaired immediately, and the corrosion rate of the pipeline is also increasing gradually. Therefore, the corresponding maintenance work should be deployed in advance for the gas pipeline, otherwise it will inevitably cause serious damage.

5. Conclusion and shortcomings

Based on the improved grey model for submarine pipeline corrosion prediction, the following conclusions are obtained:
(1) The improved grey model in this paper is based on the use of appropriate translation and sine transformation to modify the conventional grey model, and is organically combined with the full use of the original series of information.

(2) The improved grey model is not only more accurate than the conventional grey model and the model of [14] in prediction. The average relative error is determined by the 5.06% of the conventional grey model and 3.77% of the model of [14] dropped to 2.61%, and the stability of the model is better.

(3) What has not been explained in this paper is the use of different translation and transformation methods, but the model prediction will fail. The specific reasons need to be further studied and explained.

(4) The same prediction model may fail to predict when faced with data sources under different backgrounds. For example, during the corrosion process of a pipeline, it is necessary to pay attention not only to the corrosion status of a small area, but also the corrosion status of the entire pipeline, and the corrosion detection value of the entire pipeline should belong to the oscillation series. The improved grey model in this paper can only predict the corrosion in a small area. Future research should focus on how to apply the grey model to pipeline corrosion data with oscillating properties.

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