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The Research on Subsidence Prediction of Soils Around Deep Foundation Pit

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Abstract: Deep foundation pit will cause settlement of surround buildings in the process of excavation. When the settlement is excessive, it will give rise to safety issues. Subsidence monitoring has become an important measure to ensure the safety of deep foundation pits. But in current subsidence monitoring engineering, the costs of wiring, unwiring and installation are particularly high. This paper proposes a portable wireless data transmission device in forecasting and early warning of settlement deformation of soils around deep foundation pits. We solve the problem by adopting the means of wireless communication to replace the cable transmission link part. The device does not rely on any personal computers. Instead, it can directly deal with the collected data through grey prediction GM (1, 1) mathematical model, neural network and interpolation model to give short-term, medium-term and long-term forecasts, respectively. Additionally it is able to set a threshold value. Once the forecast data reach the threshold, the device can issue alert and achieve the target of reminding technicians, so as to provide reliable basis to prevent and reduce disasters. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Portable, Wireless, Subsidence, Prediction, Deep foundation.

1. Introduction

Urban space becomes increasingly limited with the rapid development of economy and urbanization. To alleviate the restrictions, people continually design buildings up into the air and down into the underground. At the same time, underground space and facilities with various functions have been developed extraordinarily, which forms the trend of three-dimensional development for urban buildings. Deep foundation pit is a very complicated and important portion in structural engineering. Its stability is not only correlated to the safety of upper main structures, but also affects the deformation of surrounding buildings. If the surrounding buildings experience large amount of settlement, it will give rise to safety issues. For example, on May 8, 2010, three adjacent dormitory buildings and aisles cracked to different extent when a deep foundation pit of underground parking lot was being excavated [1]; On October 17, 2013, the construction of a deep foundation pit led to excessive settlement of the foundation. Consequently, five buildings in the front of the foundation were all damaged, such as some wall cracked, some roof leaked, etc. [2].

The occurrence of these accidents, on one hand, is due to soil conditions and construction technology etc, on the other hand, is owing to lack of warning and control system appropriately established on site. At present, most construction sites of deep foundation pits have had the instruments and equipment monitoring subsidence, while are lack of the device predicting subsidence and issuing early warning. When technicians find that the deformation of deep foundation pits reaches the specified threshold, it has already been helpless at this time. Additionally, geotechnical engineering itself is very complicated where the characteristics of most soils are uneven. As a result it is hard to accurately grasp the geological formation and does not have accurate quantitative results for the stability of foundation pit, the internal force and deformation of retaining structure, or the impact of surrounding strata displacement on buildings and underground pipelines and corresponding protection analysis. The mechanical properties of soils are also difficult to be comprehensively reflected in engineering calculation [3], such as large amount of soft clay in the soft soil area in Tianjin, which have the properties of creep, relaxation, flow, and long-term rheological properties. So the theory of the foundation stability and structure deformation has considerably limitations in engineering practice. When large scale finite element software is employed to simulate the subsidence, it is difficulty to choose a reliable mechanical model as well as mechanical parameters that are in line with the actual situation. But if the deformation of buildings surrounding deep foundation pit is deemed as a system engineering [4], by using the construction monitoring data to predict the trend of deformation, the above mentioned problem can be solved to some extent and consequently it can improve the supervision of construction process and ensure the safety of deep foundation pit.

At present, the method of data transmission via cable is used in monitoring the deformation of deep foundation pit and surrounding buildings during the excavation process. This method has advantages of efficiency and good accuracy in data transmission and it is also a well established technology. However, with the increasing excavation depth of deep foundation pit, numbers of sensors and amount of cables required dramatically increase and workload of cable connection and disconnection is laborious. This increases the test cycle, reduces the efficiency, and even leads to difficulty of wiring cables with thousands of meters. Numerous cables are chaotic and prone to be mistakenly connected, which can result in significant losses in later data process. Moreover, long cable has large resistance, which affects the sensitive coefficient of strain sensors. If no effective measures are taken to correct the error, it will lead to smaller test results which are unfavorable to the safety evaluation of the structure. Additionally, as test cycle of deep foundation pit is long, over night vigilance on site is required in order to prevent vandalism and theft [5].

Along with the development of information technology, deep foundation pit engineering pay more and more attention to the method and technology of advanced monitoring. Monitoring technology is developing in the direction of systematic, remote distance, automatic, so as to realize real-time data acquisition and data analysis. People constantly improve the accuracy of data analysis and effectiveness of data feedback. But current methods of inspection need to collect data through connection of PC so as to process the data, especially for data forecasting and early warning analysis. If not, technical personnel face a large amount of data signal of real time monitoring and has to analyze their dynamic trend, which is an extremely complicated and time consuming process. This paper develops a kind of portable wireless data transmission equipment to facilitate settlement prediction of surrounding buildings and early warning analysis in construction of deep foundation pit. This device does not rely on PC and can directly deal with the data collected through grey prediction GM (1, 1) mathematical model, neural network and interpolation mathematical model to forecast. By setting a threshold value, the system can issue alert to remind technical personnel, when the collected or predicted data reach the threshold, so as to provide reliable basis for informatization construction as well as disaster prevention and reduction. This paper introduces the device from the perspectives of working principle and the principles of three mathematical models in forecasting and early warning analysis. The specific technical route is shown in Fig. 1.

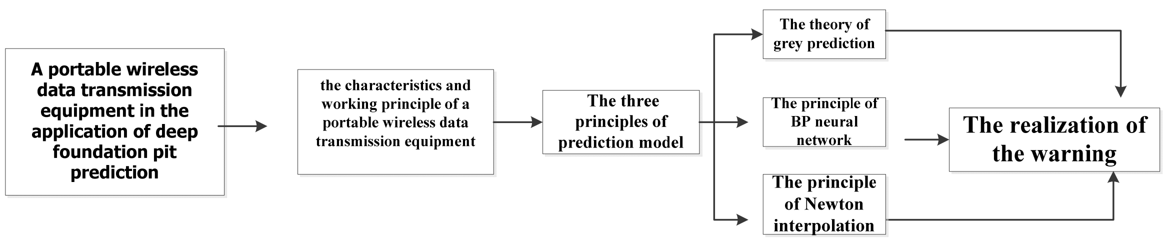

Fig. 1. Technical route.

2. The Characteristics and Working Principle of Portable Wireless Data Transmission Equipment

The portable wireless data transmission equipment can not only facilitate construction personnel to gain accurate construction data but also largely promote construction informatization. According to actual engineering demand, the wireless transmission equipment has the characteristics of small volume, low transmission power and good electromagnetic compatibility of sensor, security, transport protocol standardization etc; The sensor has good performance in dustproof, waterproof, moisture-proof, anti-corrosion, mechanical shock resistance and other protective properties, and it also has the advantages of stable work, reliable performance, low failure rate [6].

The specific working principle of the device is that the power is supplied by batteries; integrated circuit of 89S51 is adopted inside insulation panels; the goal of signal acquisition is achieved by collecting signal through the system of receiving circuit to the sensor; the signal is transmitted to the A/D converter and undergoes "noise" process by CPU, and then shows in the display. Two buttons of switch on and off are provided to control whether the display starts to work. By writing suitable program codes in the gray prediction GM (1, 1) model, the BP neural network and the interpolation model, the data can be processed and the goals of short-term, medium term and long term forecasts can be achieved respectively. Three buttons are set to control on and off of three programs and show the results in the display. Once the collected data or predicted data reach the threshold, a LED light turns red. On this basis, the integrated circuit is schematically shown in Fig. 2 [7].

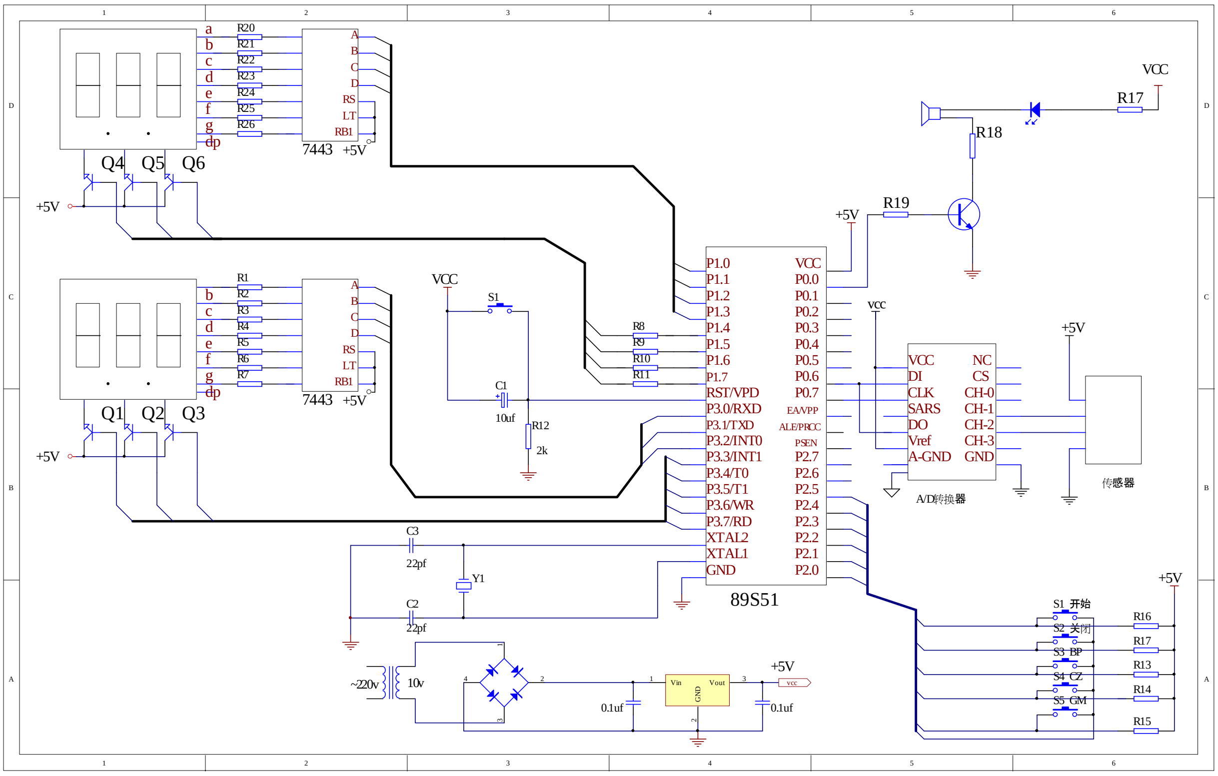

Fig. 2. The schematic diagram of the integrated circuit.

3. The Principles of Three Prediction Models

3.1. The Theory of Grey Prediction

Grey prediction was proposed by Chinese researcher Julong Deng [8]. The model is suitable for small sample sizes and scarce information and is well applied to the short-term prediction of engineering. The specific procedure of the principle is:

1) accumulation generation sequence $X^{(1)}$ is calculated as the following on the basis of the original sequence $X^{(0)}$,

$$X^{(1)}(i) = \sum_{m=1}^{n} X^{(0)}(m), \tag{1}$$

2) On the basis of $X^{(1)}$, together with the method of least squares, the parameters of the model are determined as follows:

$$\hat{a} = \begin{bmatrix} a \\ u \end{bmatrix} = (B^T B)^{-1} B^T Y_N, \tag{2}$$

where

$$B = \begin{bmatrix} -\frac{1}{2}(X^{(1)}(1) + X^{(1)}(2)) & 1 \\ -\frac{1}{2}(X^{(1)}(2) + X^{(1)}(3)) & 1 \\ \dots & \dots \\ -\frac{1}{2}(X^{(1)}(n-1) + X^{(1)}(n)) & 1 \end{bmatrix}, \tag{3}$$

$$Y_N = \begin{bmatrix} X^{(0)}(2) \\ X^{(0)}(3) \\ \ldots \\ X^{(0)}(n) \end{bmatrix}, \quad (4)$$

3) Establishing a prediction model to get incremental sequence:

$$X^{(1)}(t+1) = (X^{(0)}(1) - \frac{u}{a})e^{-at} + \frac{u}{a}, \quad (5)$$

4) Using residual analysis to check the model;

5) Changing in the future according to the system to determine the upper and lower bounds of the predicted value and to determine the grey plane;

6) Using model to forecast. The above prediction is based on the accumulation generation sequence $X^{(1)}$. By using the reduction method, it can be originated to the prediction based on original sequence $X^{(0)}$. The specific flow chart is as shown in Fig. 3.

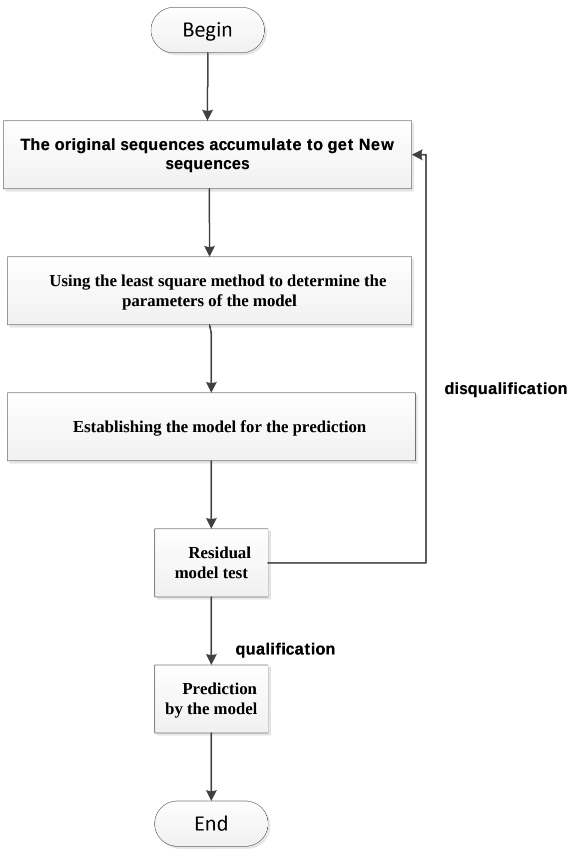

Fig. 3. The flow chart of grey prediction.

Part of Matlab core code is as follows:

```
function pre=GM11(x)
% x, Modeling sequence x=[x(1),x(2),...,x(n)]
% pre is the prediction value which gets from the model of GM(1,1),  it is that  x get to x(n+1)
n=length(x);
x1=cumsum(x);
z1=(x1(1:n-1)+x1(2:n))/2;
Y=x(2:length(x))';
B=[-z1',ones(n-1,1)];
A=(B'*B)\B'*Y; % the parameter a, b become the Vector group in the model of GM(1,1)
beta=A(2)/(1+.5*A(1));
alpha=A(1)/(1+.5*A(1));
% After the initial sequence x0 (k) to simulate the sequence of change with time t
f=@(t)(beta-(alpha)*x(1))*exp(-(A(1)*(t-2)));
pre=f(n+1);
```

3.2. The Principle of BP Neural Network

BP neural network is a nonlinear, multilayer feedforward, reverse recursive correction weight neural network. It has strong nonlinear mapping ability, self-learning adaptive ability, fault tolerant and generalization ability. It can learn mapping relationship, memorize the learned content in the network, perform automatic error correction and apply the learned results to new knowledge. The model view of BP neural network is a topology, including the input layer, hidden layer and output layer, among which, the input layer and output layer are only one layer, while the hidden layer has multilayer [9]. Sample data get to the output layer by mapping with the hidden layer, and eventually are processed to get the output of the network. The flow chart of the BP neural network is as shown in Fig. 4.

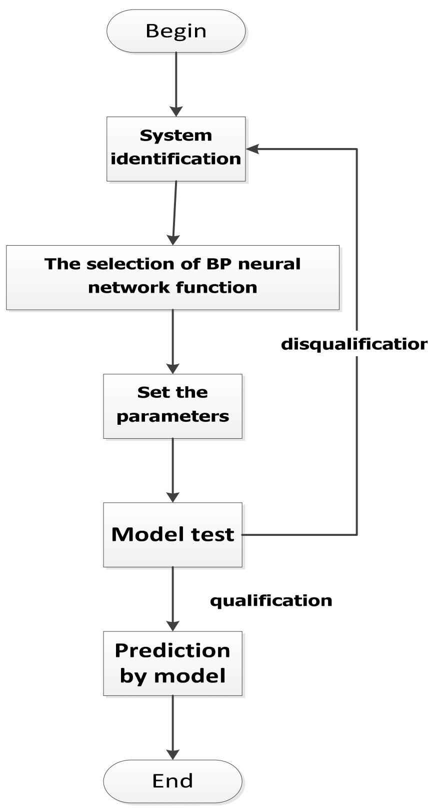

Fig. 4. The flow chart of BP neural network.

Matlab numerical simulation of prediction program is as shown below:

```
% The following six lines is the core of BP network
% They are a weight (threshold) on the basis of energy function principle of negative gradient descent for each step of the dynamic adjustment
    Delta2=Error;
    Delta1=W2'*Delta2.*HiddenOut.*(1-HiddenOut);
    dW2=Delta2*HiddenOut';
    dB2=Delta2*ones(SamNum,1);
    dW1=Delta1*SamIn';
    dB1=Delta1*ones(SamNum,1);
    % The weights between hidden layer and output layer and the threshold value
    W2=W2+lr*dW2;
    B2=B2+lr*dB2;
    % The weights between input layer and hidden layer and the threshold value
    W1=W1+lr*dW1;
    B1=B1+lr*dB1;
end
```

3.3. The Principle of Newton Interpolation

In practical engineering, functions are often established by using some isolated data. This method is called interpolation and is suitable for long-term prediction. It is assumed that $y = f(x)$ which has definition in $[a,b]$, and the corresponding values at the valid points are: $y_i = f(x_i)$ (*i=0, 1…n*). If there exists a simple function $P(x)$, in which $P(x_i) = y_i$ (*i=0, 1…n*), $P(x)$ is referred to as the interpolation function of $y = f(x)$. x_i is called interpolation node. The interval including interpolation nodes is called interpolation interval. $P(x) \in P_n[a,b]$, namely,

$$P(x) = a_0 + a_1 x + a_2 x^2 + ... a_n x^n , \qquad (6)$$

where a_i is real number and $P(x)$ is known as the interpolation polynomial. The corresponding interpolation is called polynomial interpolation. On this basis, Newton interpolation,

$$\begin{aligned} N_n(x) &= f(x_0) + f[x_0, x_1](x - x_0) + \\ & f[x_0, x_1, x_2](x - x_0)(x - x_1) + \\ & ... f[x_0, x_1 ... x_n](x - x_0)(x - x_1)...(x - x_{n-1}) \end{aligned} , \qquad (7)$$

is implemented. Considering that errors may increase as the interpolation is raised to higher order due to "morbid matrix" of interpolation coefficients [10], it often uses quartic interpolation functions to meet the requirement of practical engineering. Specific procedure of the prediction is as shown in Fig. 5.

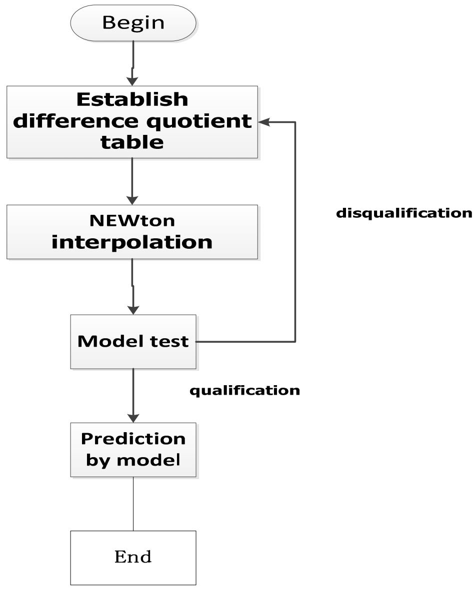

Fig. 5. The flow chart of Newton interpolation.

Part of Matlab core code is as follows:

```
y0=[x1,x2,x3…xn];
% After wavelet noise monitoring data
n=length(y0)
% Number of days
x0=1:n;
A=polyfit(x0,y0,4);
% Four times the interpolation
y6=poly2str(A,'x0')
% Newton interpolation polynomial function
A333=polyval(A,i)  %
The I day I predicted
A334=polyval(A,i+1)…
%the predicted value of i+1 day
A335=polyval(A,i+j)
% the predicted value of i+j day
```

4. The Realization of Warning

The increase of settlement greatly impairs the safety of the buildings surround deep foundation pits. It not only adversely influence on the surround environment, but also negatively impact against the property security. Therefore, it is particularly important to control the cumulative settlement. In order to promote the informationization construction, enable technical personnel on site to further understand and master the prediction methods, and more effectively control the settlement of buildings surrounding deep foundation pits, the appropriate programs are written, in which, the LED light will turn red to alert technical personnel once the monitoring data reach the threshold,. At this moment measures should be taken, when necessary, to reduce occurrence of losses. For the convenience of illustration, this paper writes it with the program code of VB [11] to demonstrate the realization of early warning. Part of the program code is as shown below.

```
Private Sub Command1_Click()
Dim i As Integer
Dim j As Integer
Dim x(1 To 10) As Single
Dim y(1 To 10) As Single
Dim z(1 To 10) As Single
For i = 1 To 10
x(i) = Val(Text1.Text) + i
y(i) = -8.7886 * 10 ^ (-9) * x(i) ^ 4 + 7.3186 * 10 ^ (-6) * x(i) ^ 2 - 0.0017891 * x(i) ^ 2 + 0.11268 * x(i) - 3.2106
z(i) = Str(y(i))
Next i
Text3.Text = z(1) & ";" & z(2) & ":" & z(3) & "; " & z(4) & ";" & z(5) & ";" & z(6) & ";" & z(7) & ";" & z(8) & ";" & z(9) & ";" & z(10)
If Val(Text2.Text) >= 10 Then
Label5.Caption = " Dangerous, please take measures "
ElseIf Val(Text2.Text) <= 10 And Val(Text2.Text) >= 5 Then
Label5.Caption = " Be careful ,it is close to the limit "
Else
Label5.Caption = "safety"
End If
For j = 1 To 10
If z(i) > 10 Then
Label5.Caption = " Dangerous, please take measures "
End If
Next j
For j = 1 To 10
If z(i) <= 10 And z(i) >= 5 Then
Label5.Caption = "Be careful ,it is close to the limit "
End If
Next j
For j = 1 To 10
If z(i) < 5 Then
Label5.Caption = "safety"
End If
Next j
End Sub
```

5. Conclusions

With the development of high-rise buildings and infrastructures in modern cities, the sizes of foundation pits become not only wider and wider but also deeper and deeper. This raises great challenge to the safety of the surrounding environment. People pay more and more attention to the subsidence deformation of surrounding buildings during the excavation of deep foundation pits. Monitoring has become the important method to ensure the safety of buildings surround foundation pits. But in inspection and tests of deep foundation pits engineering, the cost of wiring, unwiring and installation is particularly high. In order to solve the problem, this paper develops a kind of wireless data transmission equipment which is based on the mathematical models of grey prediction GM (1, 1), neural network and the interpolation prediction to assist technical personnel analyzing deformation of the deep foundation pits. The device also has the function of early warning. Once the monitoring data arrive at specified thresholds, the LED lights can issue alarm signal to technical personnel, so as to provide reliable basis for informatization construction as well as disaster prevention and reduction.

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