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# *Integrity Evaluation of Pile Based on Grey Clustering Theory*

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***Keywords:*** Grey clustering theory, Sound wave testing, Integrity evaluation, Large diameter pile.

***Abstract:*** The pile integrity, which is used as a comprehensive index to reflect the relative change of pile section size, and the compactness and continuity of pile material, has a great influence on the bearing capacity of the pile foundation, therefore, it is necessary to test and evaluate the pile integrity. In this paper, based on the basic principle and the measured data of sonic pile measurement, the sound time, sound velocity, amplitude and main frequency are determined as the evaluation factors, while the grey clustering theory is used to construct the model to evaluate the integrity of pile foundation and determine the weight of each evaluation factor, thus analyzing and evaluating the integrity of large diameter pile. After the comparison with the field measured ultrasonic testing data and the fuzzy mathematics evaluation method, it is found that this method with simple calculation method has better feasibility and applicability. Compared with the traditional evaluation method, it can overcome the shortcomings of the single index evaluation in the traditional evaluation method. With the certain objectivity, it has better reliability for judging whether the pile body has defects.

## 1. Introduction

Due to the difficult construction, complex process and strong concealment, the concrete cast-in-place pile is more likely to produce holes, cracks, intercalation, necking and other defects in the construction process, which poses a serious threat to the safety and durability of the building. The acoustic wave transmission method is an effective way to detect the defects of concrete cast-in-place piles and evaluate their integrity [1]. Wang Mengchi et al [2] have used the method of combining the model pile test with field test to analyze the shortcomings of acoustic wave transmission method in the detection of pile integrity. Based on a large amount of field detection data, Hui Bin et al [3] have analyzed the main influencing factors of acoustic wave transmission method in detecting the pile integrity. By using the engineering example, Guo Yong et al [4] have compared the low-strain reflection wave detection with the acoustic wave transmission detection. Du Shichao et al [5] have discussed the application of acoustic wave transmission method in special climate conditions in alpine regions. According to the comparative study, Yu An et al [6] have found that the detection accuracy can be improved through the combination of the ultrasonic transmission method and the ground strain reflection wave method in a longer cast-in-place pile. Based on the engineering example, Meng

Juntao et al [7] have verified the accuracy of detecting the quality of concrete cast-in-place piles by using the acoustic wave transmission method.

At present, the judgment of pile integrity mainly depends on the technology and experience of testing technicians, whose result is too subjective, thus bringing uncertain factors to the evaluation of pile foundation integrity. Many scholars have combined the methods of fuzzy mathematics, nonlinear least squares, BP neural network, analytic hierarchy process and grey theory with the acoustic wave transmission method to evaluate and predict the pile integrity [8-12]. In this paper, based on the basic principle and the measured data of sonic pile measurement, the sound time, sound velocity, amplitude and main frequency are determined as the evaluation factors, while the grey clustering theory is used to construct the model to evaluate the integrity of pile foundation and determine the weight of each evaluation factor, thus analyzing and evaluating the integrity of large diameter pile. Based on the comparison with the field measured ultrasonic testing data and the fuzzy mathematics evaluation method, it is found that this method with simple calculation method has better feasibility and applicability. Compared with the traditional evaluation method, it can overcome the shortcomings of the single index evaluation in the traditional evaluation method. With the certain objectivity, it has better reliability for judging whether the pile body has defects.

## 2. The Theoretical Basis of the Detection and Evaluation Methods

### 2.1. Grey Clustering Evaluation Method

Grey system is named according to the cybernetics that people's usage of colors to describe their cognition degree of things, and "grey" indicates that some information is clear, while some information is fuzzy, and the corresponding system is called grey system. The purpose of studying grey system is to realize the exact cognition and description of real things, and its method is to study the development and generation of accurate information in the absence of information. Grey clustering means that the whitening rights of clustering objects for different clustering indicators are summed up according to several grey types, and the types of cluster objects are judged by calculating the comprehensive effect of all indexes, thus finally obtaining the comprehensive evaluation results of the evaluation objects [13, 14].

### 2.2. Establishment of Grey Evaluation Set

The unit is denoted by $i$, $i \in I = \{1,2,3....n\}$, $I$ is called the set of evaluated units.

The project is denoted by $j$, $j \in J = \{1,2,3....m\}$, $J$ is called the set of evaluated units.

The grey type is denoted by $K$, $k \in K = \{1,2,3.... f\}$, $K$ is called the set of evaluated grey type. When K=1, this grey type is good; when $k = f$, this grey type is poor.

The system composed of the three sets of *I*, *J* and *K* is called grey evaluation system.

### 2.3. Establishment of Sample Matrix of Grey Evaluation

$d_{ij}$ is ordered as the sample of unit *i* for the project *j*, $i \in I$, $j \in J$, thus D is the evaluated matrix:

$$d_{ij} = D = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1m} \\ d_{21} & d_{22} & \cdots & d_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ d_{n1} & d_{n2} & \cdots & d_{nm} \end{bmatrix} \tag{1}$$

### 2.4. Determination of Grey Whitenization Weight Function

$f_j^k(d_{ij})$ is the whitenization function of the *k*-th grey type of the *j*-th evaluated project, and there are three kinds of these functions, including the whitenization weight function of upper-limit measurement effect, the whitenization weight function of moderate measurement effect and the whitenization weight function of lower-limit measurement effect. The specific analysis is as follows:

Whitenization weight function of upper-limit measurement effect

$$f_j^k(d_{ij}) = \begin{cases} \frac{d_{ij}}{x_j^k}, d_{ij} \in [0, x_j^k] \\ 1, d_{ij} \in [x_j^k, \infty] \end{cases} \tag{2}$$

Whitenization weight function of moderate measurement effect

$$f_j^k(d_{ij}) = \begin{cases} \frac{d_{ij}}{x_j^k}, d_{ij} \in [0, x_j^k] \\ -\frac{d_{ij}}{x_j^k} + 2, d_{ij} \in [x_j^k, \infty] \end{cases} \tag{3}$$

Whitenization weight function of lower-limit measurement effect

$$f_j^k(d_{ij}) = \begin{cases} 1, d_{ij} \in [0, x_j^k] \\ -\frac{d_{ij}}{x_j^k} + 2, d_{ij} \in [x_j^k, 2x_j^k] \end{cases} \tag{4}$$

Where, $x_j^k$ is the threshold value, and $d_{ij}$ is the initial valued sample matrix after initialization.

### 2.5. The Formula of Grey Clustering Evaluation

$\sum_{j=1}^{m} x_j^k$ Is the global sum of the threshold value of whitenization function.

$\omega_j^k = \frac{x_j^k}{\sum_{j=1}^{m} x_j^k}$ is the reduction coefficient of whitenization function.

$\sum_{j=1}^{m} f_j^k(d_{ij})\omega_j^k$ as the global sum of the converted whitenization value is denoted as , whose significance is the clustering evaluation of grey type belonging to the unit *i*.

Its computational formula is as follows:

$$\sigma_i^k = \sum_{j=1}^{m} f_j^k(d_{ij})\omega_j^k,\ \ i = 1,2,3\ldots n,\ \ k = 1,2,3,4 \tag{5}$$

### 2.6. Final Clustering Evaluation

$$\sigma_i^k = \max\left\{\sigma_i^k\right\},\quad k = 1,2,3\ldots f \tag{6}$$

Thus the grey type of the unit *i* is called *k*.

## 3. Engineering Example Analysis

### 3.1 .Basic Situation

In this paper, an engineering pile in the Reference [15] is taken as an example to conduct the analysis and calculation, and the results are compared with the results of using fuzzy mathematical method and field core sampling in the Reference [15]. The diameter of the pile is 1500mm, with the pile length of 17.9m, and the concrete strength of the pile body is C25, while the pile body is embedded with three pipe measuring tubes, which are distributed in equilateral triangle. Each point is measured at every 400mm in each section, with the ranging of 985mm, and the data of its acoustic parameter are shown in Table 1.

Table 1: Raw data of sound wave detection for engineering pile [15]

| Depth (m) | Sound Velocity (km•s$^{-1}$) | Amplitude (dB) | Sound Time (μs) | Main Frequency (kHz) | Depth (m) | Sound Velocity (km•s$^{-1}$) | Amplitude (dB) | Sound Time (μs) | Main Frequency (kHz) |
|---|---|---|---|---|---|---|---|---|---|
| 0.3 | 4.54 | 93.5 | 217.0 | 71.3 | 9.5 | 3.78 | 80.2 | 260.6 | 75.9 |
| 0.7 | 4.50 | 89.9 | 219.0 | 45.2 | 9.9 | 3.67 | 78.6 | 268.4 | 38.1 |
| 1.1 | 4.62 | 96.0 | 213.0 | 73.6 | 10.3 | 3.36 | 75.8 | 293.2 | 34.8 |
| 1.5 | 4.65 | 97.4 | 212.0 | 75.9 | 10.7 | 3.72 | 82.1 | 264.8 | 68.7 |
| 1.9 | 4.48 | 98.3 | 220.0 | 73.6 | 11.1 | 2.92 | 89.7 | 337.3 | 23.0 |
| 2.3 | 4.42 | 94.8 | 223.0 | 50.6 | 11.5 | 3.46 | 76.4 | 284.7 | 61.2 |
| 2.7 | 4.44 | 93.5 | 222.0 | 73.6 | 11.9 | 3.12 | 91.4 | 315.7 | 53.4 |
| 3.1 | 4.73 | 94.1 | 208.4 | 73.6 | 12.3 | 3.57 | 83.4 | 275.9 | 32.4 |
| 3.5 | 4.50 | 100.5 | 219.0 | 77.8 | 12.7 | 4.08 | 92.1 | 241.4 | 48.9 |
| 3.9 | 4.64 | 94.1 | 212.4 | 73.5 | 13.1 | 4.48 | 96.7 | 220.0 | 73.6 |
| 4.3 | 4.44 | 98.3 | 222.0 | 75.9 | 13.5 | 4.48 | 100.5 | 220.0 | 71.3 |
| 4.7 | 4.60 | 97.0 | 214.0 | 71.6 | 13.9 | 4.56 | 101.1 | 216.0 | 75.9 |
| 5.1 | 4.58 | 99.8 | 215.0 | 73.6 | 14.3 | 4.62 | 104.4 | 213.0 | 73.6 |
| 5.5 | 4.74 | 100.5 | 207.9 | 75.9 | 14.7 | 4.76 | 99.1 | 207.0 | 74.6 |
| 5.9 | 4.47 | 97.9 | 220.2 | 71.3 | 15.1 | 4.79 | 97.0 | 205.6 | 75.9 |
| 6.3 | 4.74 | 93.5 | 208.0 | 76.4 | 15.5 | 4.83 | 98.3 | 204.0 | 57.6 |
| 6.7 | 4.62 | 98.3 | 213.0 | 72.5 | 15.9 | 4.88 | 99.8 | 202.0 | 71.6 |
| 7.1 | 4.60 | 96.5 | 214.0 | 73.6 | 16.3 | 4.65 | 100.8 | 212.0 | 78.2 |
| 7.5 | 4.56 | 101.4 | 216.0 | 73.6 | 16.7 | 4.52 | 100.5 | 217.9 | 75.9 |
| 7.9 | 4.82 | 95.4 | 204.2 | 71.3 | 17.1 | 4.46 | 97.4 | 220.9 | 71.3 |
| 8.3 | 4.58 | 95.1 | 215.0 | 27.6 | 17.5 | 3.05 | 94.1 | 323.0 | 74.1 |
| 8.7 | 4.56 | 93.5 | 216.0 | 54.6 | 17.9 | 2.61 | 85.7 | 377.0 | 66.4 |

The following results are obtained after the analysis:
$V_m$=4.294 (mean value of sound velocity) $A_m$=94.096 (mean value of amplitude)
$T_m$=234.548 (mean value of sound time) $F_m$=64.475 (mean value of frequency)
$V_s$=0.572 (standard deviation of frequency) $A_s$=6.877 (standard deviation of amplitude)
$T_s$=39.575 (standard deviation of sound time) $F_s$=16.166 (standard deviation of sound time)

According to the raw data of sonic pile measurement in Table 1, it can be seen that there are anomalies in sound time, frequency, sound velocity and amplitude when the pile is at 8.3m to 12.7m; there are anomalies in sound time and sound velocity at 17.5m to 17.9m, but the amplitude and frequency are normal. The above two places are judged as defects by relying on experience. However, at the places of 0.7m and 2.3m, there is only abnormal frequency, and the sound time, sound velocity and amplitude are normal according to the normal judgment, thus if it is judged by experience, it is easy to think that the measurement instrument produces errors, while the two places of 0.7m and 2.3m are judged to be normal without defects.

### 3.2. Establishment of Grey Clustering Evaluation Set

In ultrasonic pile measurement, the basic acoustic parameters include the sound time, sound velocity, amplitude and frequency.

Therefore,

The set of evaluation project is denoted by j = J∈{sound velocity, amplitude, sound time and frequency}.

The set of evaluation unit is denoted by $i \in I = \{1,2,3,4\}$, namely, the four measuring point units of section 0.7m (Unit 1), 2.3m (Unit 2), 10.3m (Unit 3) and 17.5 (Unit 4)

The set of evaluation grey type is denoted by k = K∈{good, general, qualified and unqualified}.

### 3.3. Establishment of the Initialization Sample Matrix of Grey Cluster Evaluation

$d_{ij}$ is ordered as the sample value of unit i for the project j, $i \in I, j \in J$.

$$d_{ij} = \begin{bmatrix} 4.50 & 89.9 & 219.0 & 45.2 \\ 4.42 & 94.8 & 223.0 & 50.6 \\ 3.36 & 75.8 & 293.2 & 34.8 \\ 3.05 & 94.1 & 323.0 & 74.1 \end{bmatrix} \tag{7}$$

### 3.4. Averaging of Sample Matrix and Threshold Values of Whitenization Weight Function

#### 3.4.1. Averaging of Sample Matrix

Because of the maxima of sound time, the increase is not favorable to the sample value, while the increases in sound speed, amplitude and frequency are beneficial to the sample value.

(1) Averaging of sound time

$$[219.0,223.0,293.2,323.0]^{T} \rightarrow \left[\frac{2T_m-219.0}{T_m},\frac{2T_m-223.0}{T_m},\frac{2T_m-293.2}{T_m},\frac{2T_m-323.0}{T_m}\right]^{T} \rightarrow [1.06,1.04,0.74,0.62]^{T} \tag{8}$$

(2) Averaging of amplitude

$$[89.9,94.8,75.8,94.1]^{T} \rightarrow [\frac{89.9}{A_m},\frac{94.8}{A_m},\frac{75.8}{A_m},\frac{94.1}{A_m}]^{T} \rightarrow [0.95,1.01,0.81,1.00]^{T} \tag{9}$$

(3) Averaging of sound velocity

$$[4.50,4.42,3.36,3.05]^{T} \rightarrow [\frac{4.05}{V_m},\frac{4.42}{V_m},\frac{3.36}{V_m},\frac{3.05}{V_m}]^{T} \rightarrow [1.05,1.03,0.78,0.71]^{T} \tag{10}$$

(4) Averaging of frequency

$$[45.2,50.6,34.8,74.1]^{T} \rightarrow [\frac{45.2}{F_m},\frac{50.6}{F_m},\frac{34.8}{F_m},\frac{74.1}{F_m}]^{T} \rightarrow [0.70,0.78,0.54,1.15]^{T} \tag{11}$$

In conclusion, the following can be obtained:

$$D = \begin{bmatrix} 1.05 & 0.95 & 1.06 & 0.70 \\ 1.03 & 1.01 & 1.04 & 0.78 \\ 0.78 & 0.81 & 0.74 & 0.54 \\ 0.71 & 1.00 & 0.62 & 1.15 \end{bmatrix} \tag{12}$$

### 3.4.2. Averaging of Threshold Values of Whitenization Weight Function

(1) Threshold value of whitenization function of sound time

In the numerical calculation of sound time, the difference between the mean of sound time and 2 times of the standard deviation of sound time is used as a criterion for judging whether there is any defect. When the confidence interval of probability specific value is used to represent $[T_m - 2\sigma, T_m + 2\sigma]$, the probability of falling in the interval is 90%, thus the remaining percentage falls outside the interval, and the percentage outside the interval is considered to be abnormal. Suppose the confidence interval of the sound time is:

$$\begin{cases} x_1^1 = T_m - 2T_s = 155.4 \\ x_1^2 = T_m - T_s = 194.9 \\ x_1^3 = T_m + T_s = 274.1 \\ x_1^4 = T_m + 2T_s = 313.7 \end{cases} \quad (13)$$

The averaging of threshold value of sound time is

$$[x_1^1, x_1^2, x_1^3, x_1^4]^T \to [\frac{2T_m - x_1^1}{T_m}, \frac{2T_m - x_1^2}{T_m}, \frac{2T_m - x_1^3}{T_m}, \frac{2T_m - x_1^4}{T_m}]^T \to [1.34, 1.17, 0.83, 0.66]^T \quad (14)$$

(2) Averaging of threshold value of whitenization function of amplitude

According to the criterion, the critical value of amplitude defect discrimination is used as reference, and the confidence interval is set as follows:

$$\begin{cases} x_2^1 = A_m + 3 = 97.096 \\ x_2^2 = A_m = 94.096 \\ x_2^3 = A_m - 3 = 91.096 \\ x_2^4 = A_m - 6 = 88.096 \end{cases} \quad (15)$$

Thus the averaging of threshold value of amplitude is

$$[x_1^1, x_1^2, x_1^3, x_1^4]^T \to [\frac{x_1^1}{A_m}, \frac{x_1^2}{A_m}, \frac{x_1^3}{A_m}, \frac{x_1^4}{A_m}]^T \to [1.03, 1.00, 0.97, 0.94]^T \quad (16)$$

(3) Averaging of threshold value of whitenization function of sound velocity

According to the criterion, the critical value of sound velocity defect discrimination is used as reference, and the confidence interval is set as follows:

$$\begin{cases} x_3^1 = V_m + 2V_S = 5.438 \\ x_3^2 = V_m + V_S = 4.866 \\ x_3^3 = V_m - V_S = 3.722 \\ x_3^4 = V_m - 2V_S = 3.15 \end{cases} \quad (17)$$

Thus the averaging of threshold value of sound velocity is

$$[x_1^1, x_1^2, x_1^3, x_1^4]^T \to [\frac{x_1^1}{V_m}, \frac{x_1^2}{V_m}, \frac{x_1^3}{V_m}, \frac{x_1^4}{V_m}]^T \to [1.27, 1.13, 0.87, 0.73]^T \quad (18)$$

(4) Averaging of threshold value of whitenization function of frequency

According to the criterion, the critical value of frequency defect discrimination is used as reference, and the confidence interval is set as follows:

$$\begin{cases} x_4^1 = F_m + 2F_S = 96.807 \\ x_4^2 = F_m + F_S = 80.641 \\ x_4^3 = F_m = 64.475 \\ x_4^4 = F_m - F_s = 48.309 \end{cases} \quad (19)$$

Thus the averaging of threshold value of frequency is

$$[x_1^1, x_1^2, x_1^3, x_1^4]^T \to [\frac{x_1^1}{F_m}, \frac{x_1^2}{F_m}, \frac{x_1^3}{F_m}, \frac{x_1^4}{F_m}]^T \to [1.5, 1.25, 1.0, 0.75]^T \tag{20}$$

In conclusion, the obtained threshold matrix of whitenization function is

$$X = \begin{bmatrix} 1.27 & 1.13 & 0.87 & 0.73 \\ 1.03 & 1 & 0.97 & 0.94 \\ 1.34 & 1.17 & 0.83 & 0.66 \\ 1.5 & 1.25 & 1 & 0.75 \end{bmatrix} \tag{21}$$

### 3.5. Determination of the Evaluation Value of Grey Clustering

#### 3.5.1. Determination of the Reduction Coefficient of Whitenization Function

$$\omega_j^k = \frac{x_j^k}{\sum_{j=1}^{m} X_j^k} \tag{22}$$

Eq. (22) is the reduction coefficient of the whitenization function $f_j^k$, so the obtained reduction coefficient matrix of the whitenization function is

$$\omega = \begin{bmatrix} 0.247 & 0.248 & 0.237 & 0.237 \\ 0.200 & 0.220 & 0.264 & 0.305 \\ 0.261 & 0.257 & 0.226 & 0.214 \\ 0.292 & 0.275 & 0.272 & 0.244 \end{bmatrix} \tag{23}$$

#### 3.5.2. Determination of Grey Clustering Evaluation Values and Grey Types for Each Unit

(1) The measuring point (Unit 1) at 0.7m is calculated as follows:

1) The evaluation value of the first grey type of Unit 1

$$f_1^k = (\frac{1.05}{1.27}, \frac{0.95}{1.03}, \frac{1.06}{1.34}, \frac{0.7}{1.5}) = (0.828, 0.922, 0.791, 0.467) \tag{24}$$

$$\sigma_1^k = \sum_{i=1}^{n} f_j^k(d_{ij})\omega_j^k = 0.731 \tag{25}$$

2) The evaluation value of the second grey type of Unit 1

$$f_2^k = (\frac{1.05}{1.13}, \frac{0.95}{1}, \frac{1.06}{1.17}, \frac{0.7}{1.25}) = (0.929, 0.95, 0.906, 0.56) \tag{26}$$

$$\sigma_2^k = \sum_{i=1}^{n} f_j^k(d_{ij})\omega_j^k = 0.826 \tag{27}$$

3) The evaluation value of the third grey type of Unit 1

$$f_3^k = (2 - \frac{1.05}{0.87}, 0.97, 2 - \frac{1.06}{0.83}, \frac{0.7}{1}) = (0.793, 0.979, 0.723, 0.7) \tag{28}$$

$$\sigma_3^k = \sum_{i=1}^{n} f_j^k(d_{ij})\omega_j^k = 0.8 \tag{29}$$

4) The evaluation value of the fourth grey type of Unit 1

$$f_4^k = (2 - \frac{1.05}{0.73}, 2 - \frac{0.95}{0.94}, 2 - \frac{1.06}{0.66}, \frac{0.7}{0.75}) = (0.562, 0.989, 0.394, 0.933) \tag{30}$$

$$\sigma_4^k = \sum_{i=1}^{n} f_j^k(d_{ij})\omega_j^k = 0.747 \tag{31}$$

In conclusion

$$\sigma_i^k = \max\{\sigma_1^1, \sigma_1^2, \sigma_1^3, \sigma_1^4\} = \max\{0.731, 0.826, 0.8, 0.747\} = \sigma_1^2 = 0.826 \tag{32}$$

That is, when k=2, Unit 1 belonging to the second grey type has general quality.

(2) By using the same algorithm of Unit 1, the calculation result of Unit 2 (the measuring point at 2.3m) is as follows:

$$\sigma_i^k = \max\{\sigma_2^1, \sigma_2^2, \sigma_2^3, \sigma_2^4\} = \max\{0.751, 0.844, 0.828, 0.746\} = \sigma_2^2 = 0.844 \quad (33)$$

That is, when k=2, Unit 2 belonging to the second grey type has general quality.

(3) The calculation result of Unit 3 (the measuring point at 10.3m) is as follows:

$$\sigma_i^k = \max\{\sigma_3^1, \sigma_3^2, \sigma_3^3, \sigma_3^4\} = \max\{0.558, 0.631, 0.782, 0.848\} = \sigma_3^2 = 0.848 \quad (34)$$

That is, when k=4, Unit 3 belonging to the fourth grey type has unqualified quality.

(4) The calculation result of Unit 4 (the measuring point at 17.5m) is as follows:

$$\sigma_i^k = \max\{\sigma_4^1, \sigma_4^2, \sigma_4^3, \sigma_4^4\} = \max\{0.677, 0.765, 0.849, 0.831\} = \sigma_4^2 = 0.849 \quad (35)$$

That is, when k=3, Unit 4 belonging to the third grey type has qualified quality.

In conclusion, the Unit 1 and Unit 2 have general quality; the Unit 3 has unqualified quality; the Unit 4 has qualified quality. According to the grey clustering evaluation, this pile is judged as a defective pile.

### 3.6. Comparative Analysis

As shown in Table 2, the results of using grey clustering theory, fuzzy mathematics and core sampling are compared.

Table 2: The pile integrity evaluated by different methods

| Unit | Grey clustering theory evaluation | Fuzzy mathematics evaluation[15] | | Core sampling results [15] |
|---|---|---|---|---|
| | | a | b | |
| Unit 1 | General | Poor | Poor | There are small pores in concrete at 0.57m-0.83m of pile body; the concretes within the 8.8m-12.6m range of the pile body are loose; the core samples within the12.6m-12.9m range of pile body are filled with a lot of slit, with low strength, and the bottom of the pile is also sandwiched with mud. |
| Unit 2 | General | Qualified | Poor | |
| Unit 3 | Unqualified | Poor | Poor | |
| Unit 4 | Qualified | Poor | Good | |

As shown in Table 2, it is feasible to use the grey cluster analysis method to evaluate the defect of the pile. It can integrate the multiple indexes, such as acoustic wave, sound velocity, amplitude and frequency to determine the general scope and severity of defects. Due to the different weights of indicators, the result of evaluation by using the fuzzy mathematics is slightly different. Therefore, compared with the fuzzy mathematics method, the grey clustering analysis method is more simple and clear.

## 4. Conclusion

According to the study in this paper, the following conclusions can be obtained:

(1) The multiple indexes including acoustic wave, sound velocity, amplitude and frequency can be integrated by using the grey clustering evaluation, thus determining the general scope and severity of defects.

(2) According to the grey clustering evaluation on the engineering pile in the example, it can be seen that the Unit 1 and Unit 2 have the general quality; the Unit 3 has unqualified quality; the Unit 4 has qualified quality, thus this pile is judged as a defective pile.

(3) According to the comparison with the core sampling test result and the fuzzy mathematics judgment method in the reference [15], it is found that the result of grey clustering evaluation is more

accurate, but for some outliers which are difficult to be judged by single index, the grey clustering evaluation method can make the original subjective judgment numeric and make the evaluation results more scientific, while due to the different weights of indicators, the result of evaluation by using the fuzzy mathematics is slightly different. Therefore, compared with the fuzzy mathematics method, the grey clustering analysis method is more simple and clear.

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## References

*[1] Zhang Yan, Liu Jinbo. Pile Foundation Handbook. Beijing: China Architecture & Building Press, 838-839, 2014.*

*[2] Wang Mengchi, Yang Zhijie. Experimental Study on Integrity of Pile Body Detecting by Acoustic Transmission Method. Site Investigation Science and Technology, 6:35-37, 2017.*

*[3] Hui Bing, Zhang Li, Miao Xi. Sensitivity analysis of Non-defective Factors in the Detection of Pile Integrity Using Acoustic Transmission Method. Highway, 9:97-99, 2017.*

*[4] Guo Yong,Wang Bingjian, Xie Mingwu. Comparison of Reflection Wave Method and Acoustic Transmission Method for Foundation Pile Detection .Low Temperature Architecture Technology, 222(42):115-119, 2016.*

*[5] Du Shichao, Kang Chunxia, Wu Xiaoguang. Application of Crosshole Sonic Logging on Pile Integrity Testing in Aipine Region. Journal of Shenyang University (Natural Science), 27 (4): 331-334, 2015.*

*[6] Yu An, Tang Hongzhi, Liu Pengmei, Zhang Liang, Zhou Yangquan. The Research on Concrete Filling Pile Defect Detection by the Analysis and Comparison of Ultrasonic Transmission Method and Reflected Wave Method. Chinese Journal of Engineering Geophysics, 12 (1): 111-117, 2015.*

*[7] Meng Juntao, Yan Shengcai, Chen Hui, Dong Chengquan, Hu Zailiang. Detection and Analysis of Quality Defects in Concrete Cast-in-place Piles by Sound Wave Transmission Method. Railway Engineering, 6: 57-60, 2014.*

*[8] Chen Xiangyang, Wang Zhixin. Application of Fuzzy Mathematics in Ultrasonic Inspection of Pile Foundation Integrity. Highway and Automotive Applications, 173: 205-207, 2016.*

*[9] Zhang Canhui, Zhang Jianlin, Xie Jianhua. Nonlinear Least squares Method for the Testing of Pile Integrity .Chinese Journal of Applied Mechanics, 23 (1): 142-145, 2006.*

*[10] Chen Huaxing, Liu Hongli. Pile Foundation Detection and BP Neural Network Diagnosis. West-china Exploration Engineering, 2007, 6: 1-4.*

*[11] Gao Yunxia. Application of Grey Theory in Prediction of Ultimate Bearing Capacity of Cosmetics with Low Strain. Xi'an: Chang'an University, 2005.*

*[12] Xu Hongye. The Application of Grey Theory and AHP in the Pile Quality Assessment. Hunan: Nanhua University, 2012.*

*[13] Deng Julong. Grey System Theory Course. Wuhan: Huazhong University of Science and Technology Press, 5-30, 1990.*

*[14] Liu Sifeng, Dang Yaoguo, Fang Zhigeng et al. Gray System Theory and Its Applications. Beijing: Science Press, 105-395, 2010.*

*[15] Huang Zhiwei. Fuzzy Comprehensive Evaluation Study on the Ultrasonic in the Integrity Testing of the Pile. Guangzhou: Guangdong University of Technology, 2008.*