Study on the Diagnostic Method for Aseismic Suitability of Ocean Platform Foundation

Junfeng Xin¹, Zhaolin Han¹, Yu Jiao¹, Bowen Zhao¹ and Zhaoxin Ren¹

¹College of Electromechanical Engineering, Qingdao University of Science and Technology, Qingdao, China
*Corresponding author e-mail: jf.xin@163.com

Abstract. The paper conducts a systematic analysis of the diagnostic method for the aseismic suitability of ocean platform foundation and constructs a theoretically diagnostic model based on the combination of the grey theory and fuzzy synthesis evaluation technique. Firstly, this model uses the grey statistics technology to establish an evaluation matrix. Then the model determines the weights of related indicators via the grey correlation analysis. In the end, the model provides a comprehensive evaluation with the fuzzy method so that all the diagnostic results are more scientific and reasonable. This paper combines with GIS technology and has successfully carried out an evaluation on the aseismic suitability of one ocean platform foundation in Bohai Bay, which verifies the scientific validity and rationality of this model.

1. Introduction
The aseismic capacity of seabed foundation is one of the factors that affect the safety of the marine engineering infrastructures such as the ocean platform. In order to avoid tilt and other accidents as well as to ensure the normal operation of the ocean platform, a scientific and reasonable evaluation on the aseismic capacity of the seabed foundation is vital. However, there is rarely any report about studies on the aseismic capacity of the ocean platform foundation [1-4].

The evaluation methods for the aseismic capacity of seabed foundation can be divided into two categories: one is the mathematical logic reasoning method based on knowledge and rules including the grey theory, synthetical index method and fuzzy comprehensive evaluation, etc.; the other is the adaptive method based on sample learning and data-drive mode, i.e. the artificial neural network and the genetic algorithm, etc. At present, the public does not have a clear understanding of the aseismic suitability of the ocean foundation while the diagnostic procedure is affected by many known and unknown factors that it is still in the grey area with typical grey and fuzzy cognitive characteristics. Thus, the grey theory and fuzzy theory are more suitable for the evaluation on the aseismic condition of the ocean foundation [2] [4].

This paper introduces a diagnostic method that is quantitative and more manoeuvrable for the aseismic suitability of ocean platform foundation based on the combination of the grey theory and fuzzy synthesis evaluation technique. And the main steps are: defining diagnostic criteria, defining the weights of relevant indicators with the grey correlation degree based on professional assessment and defining the corresponding fuzzy evaluation matrix with the grey statistical technique; concluding the final diagnosis based on the combination of confirmed weights and the fuzzy evaluation matrix.
2. Analysis of the diagnostic factors of the aseismic suitability of the ocean foundation [2][5][6]

2.1 The landform indexes
A survey of the earthquake disasters confirms that the protruding mountain spur and the towering hill and structure on or near steep slopes suffer more damages than structure on flat foundation during an earthquake [2]. The influence on the local micro topography is either the consequence of the resonance of the protruding mountain caused by the earthquake and the amplification effects of the seismic wave’s topography; or the consequence of the ground displacement, the amplified velocity and accelerated velocity caused by multiple reflections of the body waves inside the protruding mountain and the steep slope.

Thus, the topography of the ocean floor has a direct impact on the possible damage caused by the earthquake, which inevitably affects the aseismic capacity of the platform foundation. The main landforms of the sea floor are gulf, long ridge, deep trench and flat abyssal plain.

2.2 Distribution index of fault
Seismic belt has a close connection with the active fault in the sense of causes. Therefore, through seismic belt we can explore and study the active fault zone. In the meantime, the existence of the active fault zone and the faulting are the fundamental factors that determine the distribution of earthquake and seismic zone. The fault has a severe impact on the stability of the engineering site. If an active fault passes through the engineering site, or even just creeps along the site, the accumulated fracture displacements over time will result in fracture, damage and end up as a disaster. If an active fault starts sudden rapid movements, violent dislocation movement may take place on the surface or places near the surface, which will result in ground instability, deformation of foundation, and eventually cause tremendous damage to the structures located across the seismogenic fault. This damage is irresistible. Thus, structures should avoid the active fault.

2.3 Distribution index of fault
The seismic response characteristic of the engineering site is also a factor that affects the aseismic suitability. In China, the elastic acceleration response spectrum is used to represent the seismic response characteristic of the engineering site. Based on this regulation, the maximum seismic impact coefficient and the characteristic period are the only two seismic parameters required to create the design spectrum curve of the engineering site.

2.4 Index of latent liquefaction
The latent seismic liquefaction on the engineering site or the surrounding area may also lead to severe disaster. The seismic liquefaction means the liquefaction of saturated loose sand caused by earthquake or unconsolidated formation. This liquefaction will result in ground damages [2] including sand blasting, water flood, ground fracture, land subsidence and slope instability, etc. The degrees of liquefaction of different areas can be categorized as mild, medium and serious.

2.5 Index of potential landslide
Landslide is a kind of serious geological disaster. During an earthquake, a submarine landslide will be a fatal blow to the ocean platform and other structures. Therefore, the potential seismic landslide on the engineering site is also a key factor to diagnose seismicity of the foundation. Based on the intensity and scale of the potential landslide, Landslide can be divided into three degrees: major, medium and small landslide threat.

3. Another section of your paper
The above analysis shows that the landform of the engineering site, distribution of faults, geologic feature of the site, latent liquefaction and potential landslide can all affect the seismic capacity of the
foundation. Based on these indexes, a model that evaluates the aseismic suitability of the ocean foundation can be constructed with a combination of the grey theory and fuzzy theory.

### 3.1 Diagnostic index set
Setting up a set of all the indexes that affect the aseismic capacity of the foundation and referring the set as the diagnostic index set \( U \):

\[
U = \{u_1, u_2, \ldots, u_n\}
\]  

\( n=5 \), \( u_1, u_2, u_3, u_4, u_5 \) represents the landform, distribution of faults, geologic feature of the site, latent liquefaction and potential landslide respectively.

### 3.2 Diagnostic degree set
The aseismic capacity of the ocean foundation can be categorized into several degrees, and these degrees form a diagnostic degree set \( V \):

\[
V = \{v_1, v_2, \ldots, v_m\}
\]  

\( m=4 \), \( v_1, v_2, v_3, v_4 \) represents the four levels of excellence which are excellent, good, average and poor respectively.

### 3.3 The grey fuzzy evaluation matrix
Supposing the number of experts working on the evaluation of the aseismic capacity of the target site is \( r \), the number of diagnostic indexes of the aseismic capacity is \( n \), the diagnostic degree is categorized as \( m \). The diagnosis of index \( j \) made by the expert \( s \) can be recorded as \( \lambda_{sj} \), and the diagnosis of the target site made by all the experts can be recorded as sample matrix \( \Lambda \):

\[
\Lambda = \begin{bmatrix}
\lambda_{s1} & \lambda_{s2} & \ldots & \lambda_{sj} & \ldots & \lambda_{s_n} \\
\lambda_{s1} & \lambda_{s2} & \ldots & \lambda_{s2} & \ldots & \lambda_{s2_n} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\lambda_{s1} & \lambda_{s2} & \ldots & \lambda_{sj} & \ldots & \lambda_{s_n} \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\lambda_{s1} & \lambda_{s2} & \ldots & \lambda_{sj} & \ldots & \lambda_{s_n} \\
\end{bmatrix}
\]  

Then defining the standard function of each diagnosis with the grey statistics method, calculating the weight \( f_1(\lambda_{sj}) \) of the \( \lambda_{sj} \) in No. diagnosis level and defining the whitening function as shown in Formula (4) to Formula (7):

\[
f_1(\lambda_{sj}) = \begin{cases}
\frac{\lambda_{sj}}{\lambda_i} & \lambda_{sj} \in [0, \lambda_i] \\
1 & \lambda_{sj} \in [\lambda_i, +\infty] \\
0 & \lambda_{sj} \in [-\infty, 0]
\end{cases}
\]  

\[
f_2(\lambda_{sj}) = \begin{cases}
\frac{\lambda_{sj}}{\lambda_i} & \lambda_{sj} \in [0, \lambda_i] \\
2 - \frac{\lambda_{sj}}{\lambda_i} & \lambda_{sj} \in [\lambda_i, 2\lambda_i] \\
0 & \lambda_{sj} \in [0, 2\lambda_i]
\end{cases}
\]
\[
\begin{align*}
f_3(\lambda_{sj}) &= \begin{cases} 
\frac{\lambda_{sj}}{\lambda_i} & \lambda_{sj} \in [0, \lambda_i] \\
2 - \frac{\lambda_{sj}}{\lambda_i} & \lambda_{sj} \in [\lambda_i, 2\lambda_i] \\
0 & \lambda_{sj} \not\in [0, 2\lambda_i]
\end{cases} \\
(f_4(\lambda_{sj})) &= \begin{cases} 
\frac{\lambda_{sj} - \lambda_{sj}}{\lambda_i} & \lambda_{sj} \in [0, \lambda_i] \\
\lambda_i - \lambda_{sj} & \lambda_{sj} \in [\lambda_i, +\infty] \\
0 & \lambda_{sj} \in (-\infty, 0]
\end{cases}
\end{align*}
\]

\(\lambda_1, \lambda_2\) in the formula represent the threshold values proposed by the expert.

According to the whitening function, calculating the grey statistics \(n_{ji}\) and the total grey statistics \(n_j\) that are used for matrix evaluation with the formula below:

\[
n_{ji} = \sum_{s=1}^{r} f_i(\lambda_{sj})
\]

\[
n_j = \sum_{j=1}^{m} n_{ji}
\]

Using the grey statistics and the total grey statistics to calculate the evaluation value \(r_{ji}\). The evaluation value forms the grey fuzzy evaluation matrix \(R\):

\[
R = \begin{bmatrix}
    r_{11} & r_{12} & \cdots & r_{1s} & \cdots & r_{1m} \\
    r_{21} & r_{22} & \cdots & r_{2s} & \cdots & r_{2m} \\
    \vdots & \vdots & \ddots & \vdots & \cdots & \vdots \\
    r_{nj} & r_{j2} & \cdots & r_{js} & \cdots & r_{jm} \\
    \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\
    r_{ni} & r_{ns} & \cdots & r_{ni} & \cdots & r_{nm}
\end{bmatrix}
\]

\[
r_{ji} = \frac{n_{ji}}{n_j}
\]

3.4 Weight sets of the index

\(n\) represents the number of diagnostic indexes for the aseismic capacity of the foundation; the impact of each index on the aseismic capacity is different, which means the weight is different. \(w_j\) represents the weight of the index No. \(j\); \(W\) represents the weight sets of the index:

\[
W = \{w_1, w_2, \cdots, w_j, \cdots, w_n\} \quad (\sum_{j=1}^{n} w_j = 1)
\]

The weight of each index can be determined with the grey correlational degree of the grey theory.

Formula (3) shows the diagnostic scores of each diagnostic index judged by the expert. The value per column in Formula (3) forms a comparison factor sequence \(U_j\). It represents the scores judged by different experts on the same index.

\[
U_j = \{\lambda_{j1}, \lambda_{j2}, \cdots, \lambda_{js}, \cdots, \lambda_{jm}\}
\]

Using the maximum value per column in Formula (3) to form the reference factor series \(U_0\), which represents the highest score judged by each expert.

\[
U_0 = \{\lambda_{\text{max}1}, \lambda_{\text{max}2}, \cdots, \lambda_{\text{max}s}, \cdots, \lambda_{\text{max}r}\}
\]
In this formula, $\lambda_{\text{max}} = \max \{\lambda_{ij}\}, j = 1, 2, \ldots, n$.
Calculating the correlation coefficient [7-10] of $U_j$ against $U_0$ with the expert $s$ with Formula (14):

$$\zeta_j(s) = \frac{\min_j \min_s |U_0(s) - U_j(s)| + \varphi \max_j \max_s |U_0(s) - U_j(s)|}{|U_0(s) - U_j(s)| + \varphi \max_j \max_s |U_0(s) - U_j(s)|}$$

(14)

$\varphi$ represents the identification coefficient, $\varphi \in [0, 1]$.
Using the identification coefficient in Formula (15) to calculate the degree of association $k$:

$$k_j = \frac{1}{k} \sum_{s=1}^{\varphi} \zeta_j(s)$$

(15)

Using the degree of association to calculate the weight of each factor $w_j$:

$$w_j = \frac{r_j}{\sum_{j=1}^{\varphi} r_j}$$

(16)

3.5 Fuzzy diagnosis
Using the fuzzy evaluation matrix and the weight set in Formula (17) to calculate the relative membership $B$ (evaluated by scores) of the aseismic suitability of associated subsea block. Note: if the difference between each evaluation degree is relatively small, calculation must be rerun

$$B = W \cdot R$$

(17)

In order to clearly separate the evaluation degree of different subsea blocks, the evaluation degrees that have been calculated can be further graded (Delphi method) and recorded as $D = (d_1, d_2, \ldots, d_m)$. $d_i$ represents the grade of the evaluation degree $v_i$. Formula (18) can calculate the score of related subsea block:

$$Z = B \cdot D^T$$

(18)

4. Organization of the Text
Seven experts (E1-E7) are invited to make a diagnosis of aseismic suitability of Bohai bay platform foundation. The number of the diagnostic index is five ($u_1-u_5$); the score range is $0 \leq \lambda_{ij} \leq 10$; the final diagnose sample from the experts is shown in Table 1.

|   | $u_1$ | $u_2$ | $u_3$ | $u_4$ | $u_5$ |
|---|-------|-------|-------|-------|-------|
| E1 | 10    | 9     | 9     | 8     | 8     |
| E2 | 9     | 8     | 10    | 9     | 8     |
| E3 | 9     | 6     | 8     | 7     | 8     |
| E4 | 8     | 8     | 8     | 7     | 8     |
| E5 | 8     | 9     | 8     | 6     | 6     |
| E6 | 8     | 8     | 8     | 8     | 5     |
| E7 | 10    | 6     | 6     | 7     | 8     |

According to the evaluation degree set above, setting the grey number and its whitening function as Figure 1.
Figure 1. The whitening functions

Taking the index $u_1$ as an example. Use Formula 4 to Formula 8 to calculate the test statistics of this platform foundation that belongs to all grey categories:

$$n_{11} = f_1(10) + f_1(9) + f_1(9) + f_1(8) + f_1(8) + f_1(10)$$
$$= 0.8889 + 1 + 0.8889 + 0.8889 + 0.8889 + 6.4445 = 8.4445$$

(19)

$$n_{12} = f_2(10) + f_2(9) + f_2(9) + f_2(8) + f_2(8) + f_2(10) = 5.5322$$

(20)

$$n_{13} = f_3(10) + f_3(9) + f_3(9) + f_3(8) + f_3(8) + f_3(10) = 1.9752$$

(21)

$$n_{14} = f_4(10) + f_4(9) + f_4(9) + f_4(8) + f_4(8) + f_4(10) = 0$$

(22)

With Formula 9, we can calculate the total grey statistics: $n_1 = 13.9519$. With Formula 10, we can calculate the evaluation value of each grey category: $r_11 = 0.4619$, $r_{12} = 0.3965$, $r_{13} = 0.1416$, $r_{14} = 0$.

Similarly, we can calculate the grey statistics $n_{ji}$, the total grey statistics $n_j$, and the evaluation value $r_{ji}$ of the other indexes. Thus, we can calculate the grey fuzzy evaluation matrix of all diagnostic indexes:

$$R = \begin{bmatrix}
0.4619 & 0.3643 & 0.4344 & 0.3224 & 0.4453 \\
0.3965 & 0.4884 & 0.3532 & 0.4634 & 0.4593 \\
0.1416 & 0.2321 & 0.2354 & 0.3342 & 0.2854 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

(23)

Picking the highest score in each line from Table 1 and form the reference factor series $U_0 = \{10, 10, 9, 8, 9, 8, 10\}$. And taking each column in Table 1 as the comparison factor series and receiving the absolute difference series in Table 2, among which $\Delta_{j(s)} = |U_0(s) - U_j(s)|$, $s = 1, 2, ..., 7$, $j = 1, 2, 3, 4, 5$.

| No. | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|-----|-----|-----|-----|-----|-----|-----|-----|
| $\Delta_1(s)$ | 0   | 1   | 0   | 0   | 1   | 0   | 0   |
| $\Delta_2(s)$ | 1   | 2   | 3   | 0   | 0   | 0   | 4   |
| $\Delta_3(s)$ | 1   | 0   | 1   | 0   | 1   | 0   | 4   |
| $\Delta_4(s)$ | 2   | 1   | 2   | 0   | 3   | 0   | 3   |
| $\Delta_5(s)$ | 2   | 2   | 1   | 1   | 3   | 3   | 2   |

In Table 2, $\min i \min s |U_0(s) - U_j(s)| = 0$, $\max i \max s |U_0(s) - U_j(s)| = 4$. In formula 14, setting the identification coefficient $\varphi = 0.5$, one can work out the correlation coefficient of index $j$ by expert $s$.

For example, taking index No. 4 and expert No. 7, because: $|U_4(7) - U_4(7)| = |\Delta_4(7)| = 3$, thus,
\[
\zeta_4(7) = \frac{0 + 0.5 \times 4}{3 + 0.5 \times 4} = 0.4
\]

(24)

With Formula 14, we can calculate all the correlation coefficients in turn as shown in Table 3.

Table 3. Correlation coefficient

| No. | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|-----|-----|-----|-----|-----|-----|-----|-----|
| \(\zeta_1(s)\) | 1   | 0.667 | 1   | 1   | 0.667 | 1   | 1   |
| \(\zeta_2(s)\) | 0.667 | 0.5  | 0.4 | 1   | 1   | 1   | 0.333 |
| \(\zeta_3(s)\) | 0.667 | 1    | 0.667 | 1   | 0.667 | 1   | 0.333 |
| \(\zeta_4(s)\) | 0.5  | 0.667 | 0.5 | 1   | 0.4 | 1   | 0.4  |
| \(\zeta_5(s)\) | 0.5  | 0.5  | 0.667 | 0.667 | 0.4 | 0.4 | 0.5  |

Based on the correlation coefficient in Table 3, with Formula 15 we can calculate the degree of association \(k_1=0.9049, k_2=0.7, k_3=0.762, k_4=0.6381, k_5=0.5191\). With Formula 16, we can calculate the weight sets of the index:

\[
W = \{0.2568, 0.1986, 0.2162, 0.1811, 0.1473\}
\]

(25)

Based on the weight sets \(W\) and the grey fuzzy evaluation matrix \(R\), with Formula 17 we can calculate the relative membership \(B\):

\[
B = W \cdot R = \{0.3931, 0.4231, 0.1342, 0.1543\}
\]

(26)

5. Conclusion

The aseismic capacity of seabed foundation makes great influence on the safety of the ocean platform. Based on the analysis of the influencing factors of the aseismic capacity of the seabed foundation, the paper has constructed a diagnostic model of the aseismic capacity of the ocean platform based on the combination of the grey theory and fuzzy synthesis evaluation technique. This paper has combined the assessment model with GIS technology and has successfully illustrated the seismic condition of an
ocean platform in Bohai Bay in a more reasonable and direct way, which has verified the scientific validity and rationality of this model. This model has more flexible and strong operability. Moreover, it has effectively overcome the public’s vague understanding of the aseismic suitability of the ocean platform foundation, which has provided reference to the safety evaluation of our country’s ocean platform foundation.

Acknowledgments
The study has been supported by Natural Science Foundation of China (Grant No.51609120), Science and Technology Plan for Shandong University (Grant No. J16LB7) and Key R & D project of Shandong Province (Grant No. 2018YFJH0704).

References
[1] L.F. Ramos and P.B. Lourenço. Modeling and vulnerability of historical city centers in seismic areas: a case study in Lisbon [J]. Engineering Structures, 2004, 26(9):1295-1310.
[2] Junfeng Xin. Seismic Suitability Evaluation Method Research on Urban Land [D]. Qingdao: Ocean University of China, 2009.
[3] Zongxiang Xiu. Deep Water Jacket Offshore Platform Security Reliability Analysis and Optimization Design. [D]. Qingdao: China University of Petroleum, 2012.
[4] Junfeng Xin. Modal Parameter Identification Technology Research on Offshore Platform based on The Stochastic Subspace Method [D]. Qingdao: Ocean University of China, 2012.
[5] GB50011-2001, 《Earthquake Resistant Design Code》[S].
[6] V. Agnesi, M. Camarda, C. Conoscenti, et al. A multidisciplinary approach to the evaluation of the mechanism that triggered the Cerda landslide (Sicily, Italy) [J]. Geomorphology, 2005, 65 (1-2):101-116.
[7] B.R. Chang. Novel grey relational measurements[C]. International Joint Conference on Neural Networks, 2001(3): 1615-1619.