Fuzzy Optimum Decision for Architectural Foundation Scheme

Ma Bin-Hui, Heng Shuai, Niu Hao-Yi, Zhao Ming-Hua

School of Civil Engineering, Hunan University of Science and Technology, Xiangtan, Hunan, 411201, China

ABSTRACT

Foundation engineering is a comprehensive geotechnical engineering problem. It is costly and time-consuming. And the construction quality is difficult to observe and determine, so is the strengthening and repairing work later. Therefore, people attach greater importance to the selection before building the foundation. This paper, based on the statistical analysis of the forms, characteristics and applicable scopes of the building foundation, establishes the hierarchical factor system and introduces the theory of fuzzy system in order to improve the traditional AHP method and to propose a more comprehensive fuzzy evaluation system combining more accurate FAHP method and interval theory together. Additionally, the basic principles and algorithm of artificial neural network are analyzed and expounded, then combine neural network and fuzzy system to build a fuzzy neural network system for selecting foundation scheme. Furthermore, simulated testing and performance analysis for the two models are conducted to offer some guidance for the project selection.

KEYWORDS: foundation scheme, Fuzzy Optimum Selection, FAHP neural network

INTRODUCTION

Foundation engineering is the basis of architectural structure, passing the load of the upper structure on to the foundation. According to statistics, the price for building the foundation accounts to 20% to 30% of the total cost, and the construction time up to 30% of the total period. Meanwhile, the foundation bears the major load and has greater underground depth, thus requiring a demanding bearing capacity, compression resistance, and stability. And its construction is more subject to the restriction of the surrounding environment and geological conditions as well. The design of
foundation will exert a significant impact on the cost, schedule, quality and safety of the entire engineering. Hence, a reasonable and optimum selection of the foundation, on the premise of meeting the normal function and safety conditions, at the same time to be well-designed, energy-saving and cost-saving, has become an urgent problem in engineering and scientific research.

Three approaches can be applied in selecting the type of foundation and its optimal scheme, and they are qualitative analysis, quantitative analysis, and the combination of qualitative and quantitative analysis. Qualitative analysis mainly relies on the practical experience, subjective judgment and analysis capabilities of the predicting personnel to deduce the nature and trends of certain object. The common methods include expert evaluation and the Delphi method, etc. While quantitative analysis, based on statistical data to build the mathematical model and calculate all indexes and numerical value of the target through certain mathematical model. AHP, and multi-objective decision model are the common methods. The major method for the combination of quantitative and qualitative analysis is expert system.

Foreign schemes and procedures of foundation selection, mainly including expert system GSS, AHP, and logical reasoning mechanism, have been gradually commercialization. For example, Ulshafer M.L.developed pile selection module based on expert system FLOPS, using a large number of database and adopting fuzzy comprehensive evaluation to select foundation.[1]Professor Tuna in Firat University of Turkey, designed software DTSA ES for dam foundation selection in silt areas.[2]

While domestical foundation selection is also developing step by step with a focus on the optimization of pile foundation. For example, He Weilian from Tongji University carried out research and discussions on the foundation Foundation in Deep-water for FAHP[3]. While Wang Jingjian from Chang'an University applied general AHP and neural network to run a comprehensive analysis for the selection of building.[4] In addition, Zhang Jinhui of Shanghai Jiaotong University, and Luo Wei of Zhejiang University used FAHP to select an optimum model for the pile foundation.

The selection methods at home and abroad still take the traditional AHP as the theoretical basis and then make summarization and analogy of the collected information. However, due to the different natures of decision-making and forecasting, and the changeable influence factors for their relevance.

In reality it is not feasible to adopt all the indexes and evaluation factors at present. In view of the above problems, this paper will improve the traditional AHP method and establish a fuzzy optimization model combining qualitative and quantitative indexes for data processing and program decision-making, and the fuzzy neural network is introduced in order to get better option for decision-making, and provide some recommendations to engineering and related scientific research.[5]
ANALYSIS OF BUILDING FOUNDATION

Characteristic analysis of foundation selection

The scheme for foundation selection should contain both specific index like cost and construction period and those vague ones like construction experience and influence on the surroundings. Combination of the two indexes not only needs a large number of exact data but also rich experience of experts.

Hierarchical structure

Therefore, this paper will conduct a comprehensive analysis of such factors as features of upper structure, hydrogeological conditions, construction feasibility and environmental impact so as to make the optimal selection through all-round contrast. First of all, make the optimal foundation as the overall objective. Then choose the construction factors, geological conditions, construction feasibility, economical efficiency, safety concern and environmental adaptability according to the characteristics of this project and take them as the criteria. Finally, further subdivide them into 27 criteria. [4]

FUZZY OPTIMAL DECISION MODEL

The building foundation has a complex condition, close relation with geographical conditions, and a great amount of information and empirical data, thus it cannot adapt to the current decision-making by relying merely on the engineering experience and limited judgement. Besides, multi-attribute decision making theory becomes increasingly of ambiguity and uncertainty in information. Therefore, this paper will adopt the fuzzy optimal selection model combining both qualitative and quantitative indexes based on the improved traditional AHP, to process the data and decide the optimizing scheme.

Hierarchical structure and initial evaluation of weights

T.L. Saaty, an American operational research expert, proposed AHP decision approach in 1970’s to make decisions on the complicated problem. It is flexible, systematic and easily operational and
This paper will combine the hierarchical factor system 1-6-27 listed in the table 2 and AHP to analyze the foundation selection.

Consider a random $n \times n$ matrix $a_{ij} > 0$, $a_{ij} = 1 / a_{ij}$ and call it reciprocal matrix. AHP judgement matrix $A$ is formed to compare in pairs, where $a_{ij}$ stands for the importance of plan $i$ to plan $j$.

\[
A = (a_{ij})_{n \times n} = \begin{pmatrix}
    a_{11} & \cdots & a_{1n} \\
    \vdots & \ddots & \vdots \\
    a_{n1} & \cdots & a_{nn}
\end{pmatrix}
\] (0.1)

Psychological research and practice show that the variation of the differential extremity in psychology compared at the same time is $7 \pm 2$, thus nine-demarcation method is adopted for measurement.

### Table 1: Foundation Selection Indexes

<table>
<thead>
<tr>
<th>Foundation Selection</th>
<th>Geological Conditions</th>
<th>Construction Feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Factors</td>
<td>Function</td>
<td>Height</td>
</tr>
<tr>
<td>Grade</td>
<td>Soil layer distribution</td>
<td>Soil liquefaction</td>
</tr>
<tr>
<td>Stories</td>
<td>bearing stratum uniformity</td>
<td>Substratum condition</td>
</tr>
<tr>
<td>Structure type</td>
<td>Construction facility</td>
<td>Transportation condition</td>
</tr>
<tr>
<td>Load distribution</td>
<td>Underground water condition</td>
<td>Construction difficulty</td>
</tr>
<tr>
<td>Uniformity</td>
<td>Regional foundation</td>
<td>Construction experience</td>
</tr>
<tr>
<td>Settlement sensitivity</td>
<td>Safety Concern</td>
<td>environmental adaptability</td>
</tr>
<tr>
<td>Economical Efficiency</td>
<td>Integral settlement</td>
<td>Surroundings</td>
</tr>
<tr>
<td>Cost</td>
<td>Integral collapse</td>
<td>Available transformation</td>
</tr>
<tr>
<td>Period</td>
<td>Differential settlement</td>
<td>Anti-seismic property</td>
</tr>
</tbody>
</table>

### Table 2: Nine-demarcation Method

<table>
<thead>
<tr>
<th>Scale</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Two elements, equalyl important</td>
</tr>
<tr>
<td>2, 4</td>
<td>Compromised scale of two adjacent scales</td>
</tr>
<tr>
<td>3</td>
<td>Two elements, one slightly important</td>
</tr>
<tr>
<td>5</td>
<td>Two elements, one obviously important</td>
</tr>
<tr>
<td>6, 8</td>
<td>Two elements, one extremely important</td>
</tr>
<tr>
<td>7</td>
<td>Two elements, one overwhelmingly important</td>
</tr>
<tr>
<td>9</td>
<td>Two elements, one overwhelmingly important</td>
</tr>
<tr>
<td>Reciprocal</td>
<td>Plan to plan is $a_{ij}$, or $1/a_{ij}$ otherwise</td>
</tr>
</tbody>
</table>
Assume A is positive reciprocal matrix, if for any random element, there is \( a_{ik} \cdot a_{kj} = a_{ij} \), then we call A is consistent matrix.

For each paired comparison matrix, the original method is applied to calculate its maximum root \( \lambda_{\text{max}} \) and feature vector \( \mathbf{w} = [w_1, w_2, \ldots, w_n] \) and have them checked, thus the consistent index \( CI \) along with its random average \( RI \) and the ratio \( CR \) are introduced.

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1} \quad (0.2)
\]

\[
RI = \frac{CL_1 + CL_2 + \cdots + CL_n}{1000} \quad (0.3)
\]

Satisfactory consistency will be achieved when it meets the following formula, namely, the allocation of the weight coefficient is appropriate.

\[
CR = \frac{CI}{RI} < 0.10 \quad (0.4)
\]

Final step is to rank order of the layers and check the total consistency.

\[
b_i = \sum_{j=1}^{n} b_j a_j, i = 1, \ldots, n \quad (0.5)
\]

\[
CR = \sum_{j=1}^{n} CI(j)a_j / \sum_{j=1}^{n} RI(j)a_j \quad (0.6)
\]

### Applying Fuzzy AHP to finalize the weights

Nine-demarcation method is commonly used in the traditional AHP for decision-making. However, it is of low accuracy and does not work with fuzzy theory. In 1965, professor L. A. Zadeh, a famous American expert on cybernetics, published a thesis called *Fuzzy Sets* in the international magazine Information and control, and initiated the concept of fuzzy set. And he introduced fuzzy math and carried it out to build the Fuzzy AHP to overcome above shortcomings of traditional AHP. In comparison, Fuzzy AHP is more convenient to determine matrix, and easy to amend the consistency, but more troublesome for evaluation. Therefore, based on the traditional AHP, this paper adopts the ScaleTransformation method to establish a fuzzy judgement matrix.

Assume there is a fuzzy matrix R, if \( r_{ij} \cdot r_{ij} = 1 \), then we call matrix R fuzzy complementary matrix. The Scale Transformation method proposed by professor Xu Zeshui will be used here.

Assume \( A = (a_{ij})_{m \times n} \) is the judgment matrix by the traditional nine-demarcation method, then through the following conversion formula:
We can get the complementary judgment matrix \( A' = (a'_ij) \). It means to compare in pairs through the preferential relation matrix \( R \) in the Fuzzy AHP.

\[
A' = \begin{pmatrix}
a_{ij} & \cdots & a_{in} \\
\vdots & \ddots & \vdots \\
a_{ni} & \cdots & a_{nn}
\end{pmatrix}
\]

(0.8)

The relation between the importance of the two factors and the weight between them can be figured out by the following formula:

\[
r_{ij} = 0.5 + (w_i - w_j) \beta, \quad 0 < \beta \leq 0.5
\]

(0.9)

### Table 3: Corresponding Indexes

<table>
<thead>
<tr>
<th>indexes</th>
<th>Grade 1</th>
<th>Grade 2</th>
<th>Grade 3</th>
<th>Grade 4</th>
<th>Grade 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>intervals</td>
<td>80-100</td>
<td>60-80</td>
<td>40-60</td>
<td>20-40</td>
<td>0-20</td>
</tr>
</tbody>
</table>

Assume \( R \) is a fuzzy matrix, if for any element, there is \( r_{ij} = r_{ik} - r_{jk} + 0.5 \), then matrix \( R \) is called fuzzy consistent matrix. In this paper, the additive consistency is applied to transform consistency and to strengthen the adjustment of preferential relation matrix into fuzzy consistent matrix.

\[
r_i = \sum_{k=1}^{n} r_{ik}, \quad i = 1, 2, \cdots, n
\]

(0.10)

\[
f_{ij} = \frac{r_i - r_j}{a} + 0.5, \quad a = 2(n-1)
\]

(0.11)

Meanwhile, the following two standards for conformance check are presented as follows[11]:

\[
M = \max \left\{ f_i - f_j \right\}
\]

(0.12)

\[
e = \frac{1}{n} \sqrt{\sum_{i=1}^{n} \sum_{j=1}^{n} (r_{ij} - f_{ij})^2}
\]

(0.13)

When \( M < 0.2 \) and \( e < 0.1 \) the fuzzy complementary matrix is more reasonable; while when \( M > 0.2 \) and \( e > 0.1 \), the consistency of fuzzy complementary matrix is poor, and needs re-evaluating.

The priority of fuzzy consistent matrix can be determined by the following formula[12]:
Finally, the sequence of matrix $R$ $W = (w_1, w_2, \ldots, w_n)^T$ is calculated to deduce the weights of each factor and convert them into the overall weight in light of the overall objective.

**Evaluation from interval theory**

Due to the complexity and systematicness of various evaluations, it is rather difficult to achieve accurate measurement and estimation by point value. Russian scholars H.Grell, K.Maruhn, and W.Rinow were among the first to use interval computation to solve the values of traditional expressions and propose the algorithm of interval numbers. Later, Japanese scholar Teruo Sunaga systematically elaborated and extended the algorithm.

This paper introduces the interval theory for property evaluation, thus changing the limitations by the previous point value, increasing the accuracy of decision-making, making the model more in line with actual engineering and enhancing its efficiency.

Assume $R$ is the real number field, then the definition of the interval number is as follows:

$$a = [a^-, a^+] = \{x \mid a^- \leq x \leq a^+, a^-, a^+ \in R\}$$

The midpoint of the interval number can be calculated as $m = (a^- + a^+)/2$, width as in $l = a^+ - a^-$ and algorithms as in $\lambda A = [\lambda a^-, \lambda a^+]$.

The establishment of a evaluation grade domain, and the introduction of interval fuzzy numbers enable each grade to have a corresponding pair of interval fuzzy numbers. The corresponding range of qualitative indexes determined by the five-level partitioning method is offered below:

Three features are showed in the process of judging: one is that the higher the index is, the more optimizing it is; another is the lower the index, the more optimizing, and yet another is that moderation is optimal. However, there are usually two types of index, benefit type and cost-effectiveness type. After marking the qualitative indexes of all factors of the projects and entering the quantitative indexes, the fuzzy relation matrix $R$ will be obtained.

Then the matrix needs to be standardized to obtain standard relational matrix $R'$.
Benefit type:

\[
\begin{align*}
  r_{ij}^- &= a_{ij}^- / \sqrt{\sum_{i=1}^{n} (a_{ij}^+)^2} \\
  r_{ij}^+ &= a_{ij}^+ / \sqrt{\sum_{i=1}^{n} (a_{ij}^-)^2}
\end{align*}
\]  

(0.15)

Cost-effectiveness type:

\[
\begin{align*}
  r_{ij}^- &= (1/a_{ij}) / \sqrt{\sum_{i=1}^{n} (1/a_{ij}^-)^2} \\
  r_{ij}^+ &= (1/a_{ij}) / \sqrt{\sum_{i=1}^{n} (1/a_{ij}^+)^2}
\end{align*}
\]  

(0.16)

Comprehensive priority for decision

Weighted arithmetic average (WAA) operator is adopted in this paper to address the weighted index of the standard relational matrix \( R' \).

Assume \( \tilde{r}_{ij} \) is the index value of a set of interval numbers, then its weighted attribute value can be calculated as follows.

\[
\tilde{z}_i = \sum_{j=1}^{m} w_j \tilde{r}_{ij}
\]  

(0.17)

Finally, the possibility degree matrix put forward by Japanese scholars Nalahara et al is applied for a comprehensive priority of the interval numbers. Possibility degree formula for comparing the size of the interval number is presented below[14]:

\[
\begin{align*}
  A &= [a^- , a^+] , B = [b^- , b^+] \\
  l(a) &= a^+ - a^- , l(b) = b^+ - b^- \\
  P(A > B) &= \min \left\{ \max \left\{ \frac{a^+ - b^-}{F^+ + F^-} , 0 \right\} , 1 \right\}
\end{align*}
\]  

(0.18)

When ranking multiple interval numbers, it requires comparing in pairs, and establishing the fuzzy complementary matrix.

\[
P = \begin{bmatrix}
  0.5 & p_{12} & \cdots & p_{1n} \\
  p_{21} & 0.5 & \cdots & p_{2n} \\
  \vdots & \vdots & \ddots & \vdots \\
  p_{n1} & p_{n2} & \cdots & 0.5
\end{bmatrix}
\]  

(0.19)
where $p_{ij}$ represents the possibility degree of $a_i > a_j$. The above formula can be converted to fuzzy consistent matrix for comprehensive priority so that an ultimate decision matrix $[w_1, w_2, w_3, ..., w_n]$ can be reached, and then decisions can be made combining with practical cases.

**FUZZY BP NEURAL NETWORK**

Artificial Neural Network (ANN) is the simplified model of human central nervous system. BP neural network usually refers to the multilayer feed forward neural network based on the error backpropagation algorithm, namely, BP algorithm. Invented by a research group led by D.E.Rumelhart and J.L.McClelland, it has currently become the widely used learning algorithm in neural network. Statistics show that about 90% application in neural network are based on this algorithm.[15][16][17]

![Neural network structure](image)

**Figure 4:** Neural network structure

BP neural network consists of an input layer, one or more hidden layer and a output layer. Every layer contains numerous nerve cells, with upper and lower ones connecting each other according to their weight. But nerve cells in the same layer have no connection. The structure of a typical three-layer BP neural network is shown in Figure 4.

BP neural network can well reflect and evaluate the complex non-linear relationship between factors and foundation types for such characteristics as fast training speed, simple structure and strong mapping capacity of non-linear relationship. Furthermore, with its strong self-learning and association ability, it is of high accuracy and requires little manual intervention and expertise.

Compared with neural network, fuzzy system is superior in its easy understanding of reasoning process, well-applied expertise and lower sample requirements. However, it’s inferior in its much manual intervention, slow reasoning and lower accuracy. If the two are combined together, they can be complementary.
Building fuzzy BP neural network

Fuzzy mathematics applies mathematical methods to research and processes fuzzy phenomena. Based on fuzzy mathematics, this paper sets up the fuzzy BP neural network, a new way to process uncertain and inaccurate problems and a powerful tool to describe brain’s processing of fuzzy information.

After initializing the network, the following calculations are needed[18].

Output calculation of hidden layer:
\[ H_j = f \left( \sum_{i=1}^{n} w_{ij}x_i - a_i \right) \quad j = 1, 2, \ldots, l \]

Output calculation of output layer:
\[ O_k = \sum_{i=1}^{l} H_j w_{jk} - b_k \quad k = 1, 2, \ldots, m \]

Error calculation:
\[ e_k = Y_k - O_k \quad k = 1, 2, \ldots, m \]

Weights renewal:
\[ w_{ij} = w_{ij} + \eta H_j (1 - H_j) x(i) \sum_{k=1}^{m} w_{jk} e_k \]
\[ w_{jk} = w_{jk} + \eta H_j e_k \quad j = 1, 2, \ldots, l \]

Threshold renewal:
\[ a_j = a_j + \eta H_j (1 - H_j) \sum_{k=1}^{m} w_{jk} e_k \]
\[ b_k = b_k + e_k \quad k = 1, 2, \ldots, m \]

Theoretically, BP learning algorithm is capable of continuous mapping of approaching arbitrary non-linear relationship, but some weaknesses do exist like rather slow rate of convergence, poor numerical stability and difficult adjustments in such parameters as learning rate, momentum coefficient and initial weight value. Whereupon, this paper adopts LM algorithm, a learning algorithm of non-linear neural network, to effectively overcome above weaknesses of BP algorithm.

Network training algorithm is Levenberg-Marquardt, and its formula is
\[ x_{k+1} = x_k - \left[ J^T J + \mu I \right]^{-1} J^T e \]

The number of nodes in the hidden layer of BP neural network has a great influence on the accuracy for prediction. With few nodes, the network can’t work well, and more training is needed and the training precision is affected. While With too many, the network overfits easily. Therefore, The best number of nodes in the hidden layer can be calculated through the formula below:
\[l < n - 1\]
\[l < \sqrt{(m + n)} + a\]
\[l = \log_2 n\]

And in this paper, the hidden layer is mainly adopted, which has strong ability in generalization and is of higher precision for prediction.

**PROJECT CASE**

**Overview of the project**

The project is planned to build at the junction of the central avenue and the crossroad in Yanghuyuan wetland park of Changsha, about 100 meters south to Qi river and 800 meters west to Xiang river. The original landscape of this area belongs to the second terrace of Xiang river, with great fluctuation in terrain. The standard height of drilling hole is 29.39~35.26 meters, with the largest fall of about 6 meters. This route is located in the lowland of Changsha, the secondary syncline of Yong’an multiple syncline, with its axis stretching 40 to 45 degree northeast up to 60 kilometers. Under the constant arch faulting, a flat-folded red basin made up of geodepression deposits came into being. And the stratum is flat with rocks orientation about 300-330°±10-20°.

**Fuzzy optimum selection**

According to the hierarchical factor system, the weight of each layer has been determined respectively and assessed in accordance with the nine scales, the result is as follows:

- A: 0.1687, 0.1720, 0.1467, 0.2020, 0.2020, 0.1087
- B1: 0.0941, 0.1615, 0.1060, 0.1100, 0.1100, 0.1534, 0.1556
- B2: 0.2173, 0.1280, 0.1867, 0.1867, 0.1867, 0.1533
- B3: 0.1898, 0.2269, 0.3730, 0.2103
- B4: 0.6667, 0.3333
- B5: 0.2556, 0.2556, 0.3426, 0.1463
- B6: 0.4375, 0.3333, 0.2292

Choose P1 strip foundation, P2 Pile-supported stand, P3 pile-raft foundation, P4 Flat raft foundation, P5 Beam plate raft foundation, P6 box foundation in turn and evaluate them comprehensively, the fuzzy score of the scheme is

- P1(0.3354, 0.4637)  P2(0.3658, 0.5020)  P3(0.3514, 0.5186)  P4(0.3306, 0.4467)  P5(0.3265, 0.4415)  P6(0.3152, 0.4585)
Standardize the matrix to obtain the possibility degree matrix, and then rank them to obtain the comprehensive evaluation value.

\[
0.1635, \ 0.1890, \ 0.1874 \\
0.1547, \ 0.1509, \ 0.1545
\]

### Fuzzy BP neural network

The neural network used in this case has double hidden layers, with 27 elements in and 1 out. The sample data are taken from the foundation selection report of Yanghu area.

The invoking format for loaded data is

\[
\text{load date input output}
\]

The invoking format of fan-in network for program building is

\[
\text{net} = \text{newff}([S1, S2, \ldots, SN], \{'\text{tansig}', '\text{logsig}', '\text{trainlm}'\})
\]

The invoking format for network training program is

\[
[\text{net, tr}] = \text{train}(\text{net}, \text{input}, \text{output})
\]

When the network training program maintains stable, the network will be simulated, and the invoking format for checking the predicting ability is

\[
\text{result} = \text{sim}(\text{net}, \text{test})
\]

Related parameters of training are

\[
\text{net.trainParam.epochs} = 100 \\
\text{net.trainParam.lr} = 0.1 \\
\text{net.trainParam.goal} = 0.0004
\]

The nodes in the hidden layer using the formula is 27-15-1. And after running the simulation test when the training stabilizes, the comprehensive evaluation value will be attained.

\[
0.1653, \ 0.1907, \ 0.1863 \\
0.1567, \ 0.1567, \ 0.1568 \\
e = -0.0006, \ -0.0018, \ -0.0006, \ 0.0024, \ 0.0024 \\
\text{perf} = \text{ms}(e) = 3.1472e-06
\]

### Comprehensive analysis

After comprehensive comparison, both fuzzy optimizing model and neural network model take pile-supported stand foundation as the premier scheme, and piled raft foundation as the alternative. And this result matches with the actual engineering, as shown in Table 5.
The Comprehensive evaluation value, which conforms to check consistency, is obtained combining the weights and assessment of fuzzy optimizing model, thus the value is reasonable and scientific. Meanwhile, the fuzzy neural network system adopts interdisciplinary neural algorithm with high efficiency and expansibility. A domestic expert system and evaluation criterion in foundation selection has not fully established. The two models offered in this paper can provide a practical testing criterion for engineering.

### REFERENCES


Foundation item: Project (51308208) supported by the National Natural Science Foundation of China
Received date: 2015−10−18; Accepted date: 2015−11−08
Corresponding author: MA Bin-Hui, PhD; Tel: 0731-58290052; e-mail: bhmahd@126.com

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