Vulnerability Assessment of Regional Geological Disasters Based on Unascertained Measurement Theory

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ABSTRACT

Based on unascertained measurement theory, a comprehensive evaluation method to propose the vulnerability of regional geological disasters was presented in this paper. The function of unascertained measure of all evaluation indexes was established, the weights for indexes was calculated by entropy weight theory, and a result of the vulnerability of regional geological disasters has been carried out using the rules of credible recognition. This method can solve a lot of unascertained problems in comprehensive evaluation the vulnerability of regional geological disasters, and also can analyse the vulnerability of regional geological disasters objectively. Furthermore, using listed 40 the regions as samples, the effectiveness were discussed by the aid of comparison with the results of comprehensive index method. The research results show that the comprehensive evaluation method of unascertained measurement presents excellent performance, high accuracy and it thus has wide applying prospect, it is an effective new way to evaluate the vulnerability of regional geological disasters.

KEYWORDS: vulnerability; geological disaster; unascertained measure; credible degree recognition criterion; entropy weight

INTRODUCTION

Vulnerability and disastrous hazard are two terms distinct from one another. Disastrous hazard refers to the comprehensive negative effects brought about by possible disasters on society, economy and ecological environment. Hazard evaluation is to measure probability (the degree of
danger) that a certain disaster may happen and the degree of destruction (vulnerability) that the disaster may lead to after it occurs. The vulnerability of regional geological disasters is about how serious a certain region is prone to be hit by the geological disasters, that is, its ability to resist against geological disasters. It indicates the vulnerability of regional geological disasters under a certain circumstance. The vulnerability of regional geological disasters is to evaluate and judge the ability to resist against the disasters in a certain area. The ability to resist against the geological disasters at the same level varies from region to region. Generally speaking, for a region with higher economic standard, less disturbance to ecological environment, better infrastructure facilities and better-civilized people, it has the stronger power to resist against geological disasters and the slighter vulnerability. Disasters’ happening depends on fragility (vulnerability) of a region and its aptness to get hit by a natural disaster. Nature is a very complex system in which disasters take place and it will be a long journey to change its aptness to get hit by disasters. It’s hard to draw a conclusion about its ultimate result. On the other hand, the vulnerability of regional geological disasters at a certain time can be reduced by the reasonable management and planning of local government. Enhancing the ability to resist against disasters in a region is essential to reduce the occurrence of natural disasters in the region [1-2].

Today, there are a variety of methods to evaluate the vulnerability of regional geological disasters, such as the extension method [1], synthesis evaluation method [2], ambiguous-synthesis evaluation method [3], analysis to main components [4], ambiguous recognition method [5] and neural web method [6]. Many as these methods are, it remains a tackle problem to analyze those unascertained factors for evaluating the regional vulnerability since they are too broad and indefinite. Fortunately, unascertained mathematics offers a better approach to it.

The theory about the unascertained information and mathematic analysis was first proposed by Wang Guangyuan in 1990 [7]. Unascertained information is a new term, neither about the ambiguous information nor the random one or the gray one. Based on it, Liu Kaidi [8] and his followers founded the mathematic theories of uncertainty measurement, and applied them into social science and natural science. Among the studies in this respect, the greatest achievement is about the application of uncertainty measurement model. This thesis is to apply this theory into the issue of regional vulnerability assessment by analyzing the various factors and quantitative analysis. According to the actual state in a certain area, a model of uncertainty measurement is set up to calculate every parameter for the measurement system, and then entropy of information is used to find out the weights on different factors of regional geological disasters’ vulnerability. The principle of credibility is finally adopted for judgment and evaluation. The model is used to evaluate the geological vulnerability of 40 districts and counties from Chongqing City in China. The comparative study with the original data shows that this approach is ideal and practical, exploring a new path to evaluation vulnerability of regional geological disasters.

**CALCULATION OF UNCERTAINTY MEASUREMENT**

If there are \( n \) \( R \) the evaluation measures, then the evaluation space \( R = \{ R_1, R_2, \ldots, R_n \} \). When \( R_i (i = 1, 2, \ldots, n) = m \), \( X = \{ X_1, X_2, \ldots, X_m \} \), then \( R_i = \{ x_{i1}, x_{i2}, \ldots, x_{im} \} \). In this equation, \( x_{ij} \) is the measure of evaluation index \( X_j \) in row \( R_i \), for each item in this sub-space, \( x_{ij} (i = 1, 2, \ldots, n; j = 1, 2, \ldots, m) \). If there are \( p \) evaluation level in box bracket \( \{ C_1, C_2, \ldots, C_p \} \), when the
evaluation space is $U = \{C_1, C_2, ..., C_p\}$. If $C_k$ \((k = 1, 2, ..., p)\) is the evaluation level of \(k\), level \(k\) is higher than level \(k+1\), which can be written as $C_k > C_{k+1}$. If $C_1 > C_2 > ... > C_k$, \(\{C_1, C_2, ..., C_p\}\) will be one part of the evaluation space $U^{[9-11]}$.

**Single Index Measures**

If $\mu_{ik} = u(x_{ij} \in C_k)$ shows that the measure $x_{ij}$ is the $k$th evaluation $C_k$

$$0 \leq \mu(x_{ij} \in C_k) \leq 1 \quad \text{(1)}$$

$$\mu(x_{ij} \in U) = 1 \quad \text{(2)}$$

$$\mu\left[ x_{ij} \in \bigcup_{l=1}^{k} C_l \right] = \sum_{l=1}^{k} \mu(x_{ij} \in C_l) \quad \text{(3)}$$

where Eq.(2) is called normalization. Eq.(3) is called allowance for addition. All items $u$ that can meet Eqs.(1)~(3) are the uncertainty measures, which can be simply put as measures.$^{[9-10]}$

If matrix $(\mu_{ik})_{m \times p}$ is an evaluation matrix of the single index measures, it can be expressed as the followings:

$$(\mu_{ik})_{m \times p} = \begin{pmatrix}
\mu_{i11} & \mu_{i12} & \cdots & \mu_{i1p} \\
\mu_{i21} & \mu_{i22} & \cdots & \mu_{i2p} \\
\vdots & \vdots & \ddots & \vdots \\
\mu_{im1} & \mu_{im2} & \cdots & \mu_{imp}
\end{pmatrix} \quad \text{(4)}$$

**Measurement of Single Index**

Index weight refers to how the measuring index will be involved in a certain assessment system. Determining the index weight is one important part in a comprehensive evaluation system. According to information theory, entropy can not only be used to measure the degree of disorderliness, but can also be used for measuring validity of information offered by the data itself. In case that the single index has been determined, i.e. it has been determined that those indexes can fall into a certain degree of classification, which means that it has been determined how important those indexes are for classification system. As a result, the entropy theory can be used to determine the weight of each index in a certain evaluation system.

If $w_j$ represents the relatively significant level that the measure $X_j$ compares with the other indexes, when $w_j$ meet $0 \leq w_j \leq 1$, and $\sum_{j=1}^{n} w_j = 1$, $w_j$ is the weight of $X_j$. $w = \{w_1, w_2, ..., w_m\}$ is the vector of index weight. Its weight can be determined by the following entropy calculation$^{[12]}$:

$$v_j = 1 + \frac{1}{\lg p} \sum_{i=1}^{p} \mu_{ji} \lg \mu_{ji} \quad \text{(5)}$$

$$w_j = v_j / \sum_{i=1}^{n} v_j \quad \text{(6)}$$
Since the matrix of the single index measure is known, we can get $w_j$ by calculating the Eqs.(4)-(6).

**Evaluation Vectors of Multiple Index Measures**

If $\mu_{ik} = u(R_k \in C_k)$, the evaluation measure $R_i$ is the $k$th evaluation $C_k$, then

$$\mu_{ik} = \sum_{j=1}^{n} w_j \mu_{ijk} \quad (7)$$

Obviously, as $0 \leq \mu_{ik} \leq 1$ and $\sum_{k=1}^{p} \mu_{ik} = 1$, Eq.(7) is to determine the uncertainty measures, $\{\mu_{i1}, \mu_{i2}, \ldots, \mu_{ip}\}$ is about the evaluation vectors $R_i$ that represent the multiple index measures$^{[9, 10]}$.

**Credibility Recognition Principle and Ordering**

The credibility recognition principle is to make a final assessment to the evaluation measures. If credibility is $\lambda$ ($\lambda \geq 0.5$), when $C_1 > C_2 > \ldots > C_p$, we get

$$k_0 = \min \left\{ k : \sum_{l=1}^{k} \mu_{il} \geq \lambda, (k = 1, 2, \ldots, p) \right\} \quad (8)$$

where Eq.(8) can get the result of the evaluation vector $R_i$ that represents the $k_0$th $C_{k0}$.

Except determining which evaluation level $R_i$ falls into, it is also required to order the vulnerability indexes of regional geological disasters in some cases. If $C_1 > C_2 > \ldots > C_p$, when $C_i = I_i$ and $I_{i} > I_{i+1}$, we get

$$q_{R_i} = \sum_{l=1}^{p} I_l \mu_{il} \quad (9)$$

where $q_{R_i}$ is the importance of evaluation vector $R_i$, then $q = \{q_{R_1}, q_{R_2}, \ldots, q_{R_p}\}$ is the important vectors of uncertainty measures. As a result, $R_i$ can be ordered from the lower vulnerability $q_{R_i}$ to the higher one.

**EVALUATION MEASUREMENT SYSTEM OF REGIONAL VULNERABILITY**

Regional vulnerability resisting against the geological disasters indicates once a disaster occurs in this region, what probable destruction will be brought to the local economy and society. It is related with the development of local economy and society as well as the consequence of the geological disasters. Choice of vulnerability indexes can be made in the following four ways$^{[13]}$.

1. The indexes can be obtained by referring to post-disaster destruction assessment system.
2. Collection of these data can be based on what the public conceive about the vulnerability.
3. The indexes can be collected from the description of the local macro-economic development.
4. They can be determined by information quantitative analysis of the disaster cases. According to
Reference 2 about the History of Disaster Records in recent 50 years since the new China was founded, the four indexes are listed below to reveal the vulnerability of regional geological disasters, they are: 

① disaster density \( X_1 \), which refers to the times of geological disasters that happened in a unit area. 
\[
X_1 = \frac{N}{S}, \quad N \text{ is the times of disasters, } S \text{ is the square meters of the area, the unit is } 1000 \text{km}^2;
\]

② frequency of geological disasters \( X_2 \), which refers to how often the disasters happened each year. 
\[
X_2 = \frac{N}{\text{years}};
\]

③ economy GDP destruction modulus (intensity) \( X_3 \), which refers to the economy destruction in unit area when the geological disasters happened, the unit is 10000 Y yuan/km², 
\[
X_3 = \frac{E_S}{S}, \quad E_S \text{ is the amount of economic loss, the unit is } 10000 \text{Yuan}, S \text{ is the square meters of the area and the unit is } \text{km}^2;
\]

④ casualties modulus \( X_4 \), which refers to the loss of casualties during the geological disasters in a unit area, the unit is person/km², 
\[
X_4 = \frac{P_S}{S}, \quad P_S \text{ is the population of casualties in the area, the unit is } \text{person}, S \text{ is the square meters of the area and the unit is } \text{km}^2.
\]

Among these four indexes, the former two focus on the frequency and times of geological disasters, revealing the degree of destruction due to the geological disasters while the latter two highlight the evaluation on loss due to the geological disasters, revealing the destruction intensity of disaster-hitting area. Classification criteria is listed in Table 1. Each evaluation function is classified and determined, falling into five levels \( \{ C_1, C_2, C_3, C_4, C_5 \} \), indicating extremely high level, very high, high, medium level, low level and extremely low level of vulnerability.

### Table 1: Classification criterion for the vulnerability evaluation indexes

<table>
<thead>
<tr>
<th>Levels</th>
<th>( X_1 )</th>
<th>( X_2 )</th>
<th>( X_3 )</th>
<th>( X_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I ( (C_1) )</td>
<td>&gt;20</td>
<td>&gt;50</td>
<td>&gt;20</td>
<td>&gt;300</td>
</tr>
<tr>
<td>II ( (C_2) )</td>
<td>10~20</td>
<td>30~50</td>
<td>10~20</td>
<td>200~300</td>
</tr>
<tr>
<td>III ( (C_3) )</td>
<td>5~10</td>
<td>5~30</td>
<td>3~10</td>
<td>150~200</td>
</tr>
<tr>
<td>IV ( (C_4) )</td>
<td>3~5</td>
<td>2~5</td>
<td>1~3</td>
<td>100~150</td>
</tr>
<tr>
<td>V ( (C_5) )</td>
<td>&lt;3</td>
<td>&lt;2</td>
<td>&lt;1</td>
<td>&lt;100</td>
</tr>
</tbody>
</table>

### CASE STUDY

Take Chongqing City for example, it has forty administrative districts and counties, which should be taken into consideration as a whole administratively so that the study would offer a better guide for geological disaster relief practice. The related measurement indexes of vulnerability in every district and county have been obtained through historic records in Table 2 [2].

### Table 2: Values of the vulnerability evaluation indexes of regional geological disasters

<table>
<thead>
<tr>
<th>Name of districts</th>
<th>( X_1 )</th>
<th>( X_2 )</th>
<th>( X_3 )</th>
<th>( X_4 )</th>
<th>Name of districts</th>
<th>( X_1 )</th>
<th>( X_2 )</th>
<th>( X_3 )</th>
<th>( X_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quzhong District</td>
<td>90.9</td>
<td>2</td>
<td>181.8</td>
<td>227.3</td>
<td>Wanzhou District</td>
<td>7.3</td>
<td>25</td>
<td>8.79</td>
<td>371.13</td>
</tr>
<tr>
<td>Dadukou District</td>
<td>42.6</td>
<td>4</td>
<td>57.4</td>
<td>106</td>
<td>Kai County</td>
<td>4.5</td>
<td>18</td>
<td>4.6</td>
<td>202</td>
</tr>
<tr>
<td>Jiangbei District</td>
<td>23.4</td>
<td>5</td>
<td>70.1</td>
<td>700.1</td>
<td>Zhong County</td>
<td>2.7</td>
<td>6</td>
<td>3.7</td>
<td>284.8</td>
</tr>
<tr>
<td>Shapingba District</td>
<td>10.4</td>
<td>4</td>
<td>0.1</td>
<td>112.3</td>
<td>Liangping County</td>
<td>3.7</td>
<td>7</td>
<td>2.3</td>
<td>53</td>
</tr>
<tr>
<td>Jiulongpo District</td>
<td>6.8</td>
<td>3</td>
<td>13.5</td>
<td>180.6</td>
<td>Yunyang County</td>
<td>8.3</td>
<td>30</td>
<td>10.2</td>
<td>173.6</td>
</tr>
<tr>
<td>Nanan District</td>
<td>21.5</td>
<td>6</td>
<td>0.3</td>
<td>197.2</td>
<td>Fengjie County</td>
<td>5</td>
<td>20</td>
<td>1.88</td>
<td>195.2</td>
</tr>
<tr>
<td>Beibei District</td>
<td>16</td>
<td>12</td>
<td>5.3</td>
<td>211.9</td>
<td>Wushan County</td>
<td>8.5</td>
<td>25</td>
<td>6.6</td>
<td>96.7</td>
</tr>
<tr>
<td>Wansheng District</td>
<td>10.6</td>
<td>6</td>
<td>1.3</td>
<td>91.9</td>
<td>Wuxi County</td>
<td>13.9</td>
<td>56</td>
<td>8.67</td>
<td>11.7</td>
</tr>
<tr>
<td>Shuangqiao District</td>
<td>108.1</td>
<td>4</td>
<td>64.1</td>
<td>216.2</td>
<td>Chengkou County</td>
<td>1.8</td>
<td>6</td>
<td>0.9</td>
<td>28</td>
</tr>
<tr>
<td>Yubei District</td>
<td>6.9</td>
<td>10</td>
<td>1.2</td>
<td>68.9</td>
<td>Fuling District</td>
<td>7.5</td>
<td>22</td>
<td>0.78</td>
<td>104.9</td>
</tr>
<tr>
<td>Banan District</td>
<td>2.7</td>
<td>5</td>
<td>2.1</td>
<td>109.3</td>
<td>Nanchuan County</td>
<td>4.6</td>
<td>12</td>
<td>3.1</td>
<td>130</td>
</tr>
<tr>
<td>Jiangji County</td>
<td>11.9</td>
<td>38</td>
<td>6.3</td>
<td>156.3</td>
<td>Dianjiang County</td>
<td>4.6</td>
<td>7</td>
<td>2.89</td>
<td>177.8</td>
</tr>
</tbody>
</table>
Mapping of Single Index Functions

According to definition of the single index function and Table 1 and Table 2, each evaluation measure can be acquired by setting up the single index functions. See the following Figure 1~4 for these single index functions.

According to the measures of the factors in Table 2 and the single index functions in Figure.1~4, we can separately get an evaluation matrix of the single index measures in forty regions of Chongqing City. Take Yuzhong District $R_{yi}$ for example, we can find out the measures of the
four factors in Table 2 and exchange them with the corresponding functions in FigS.1-4, by calculation we get the following matrix of $R_{01}$

$$
(\mu_{jk})_{4x5} =
\begin{bmatrix}
0 & 0 & 0 & 0 & 1 \\
1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0.3027 & 0.6973 & 0 \\
\end{bmatrix}
$$

(10)

### Calculation of Multiple Index Measurement Matrix

Each evaluation index weight can be determined by solving Eqs. (1)~ (6). For Yuzhong District, its entropy weight of $R_{01}$ equals as that: $w_i = \{0.2763, 0.2763, 0.2763, 0.1711\}$. According to its single index matrix and Eq.(7), the evaluation vector of multiple index measurement $R_{01}$ becomes $\{0.2763, 0, 0.0518, 0.1193, 0.5526\}$. By equal-weight calculation in Reference [2], $R_{01}$ is $\{0.2500, 0, 0.0757, 0.1743, 0.5\}$.

### Credibility Recognition

If credibility recognition $\lambda = 0.75$, through observing the vector Eq. (7) for multiple index measurement and the principle of credibility evaluation Eq. (8) in small-large order, when $k_0 = 1 > \lambda$, we figure out that the vulnerability level of $R_{01}$ falls into level I while if observing from large to small order and when $k_0 = 1 > \lambda$, the vulnerability of $R_{01}$ falls into level I as well. The result is the same case by equal-weight calculation. Now that we get the similar results in two different evaluation approaches and we can safely sum up that the regional vulnerability of Yuzhong District $R_{01}$ is categorized into level I, which belongs to very hazardous level. One by one, we make evaluation from $R_{01}$ to $R_{05}$, comparing the results with those from Reference [2] by equal-weight scoring. See Table 3 for detailed comparison.

### Table 3: Comparison of the results of uncertainty measurement evaluation and integrated scoring mean evaluation

<table>
<thead>
<tr>
<th>Name of Regions</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_4$</th>
<th>$C_5$</th>
<th>Level</th>
<th>Level determined$^{[2]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dadukou District</td>
<td>0.1900</td>
<td>0.3011</td>
<td>0.0089</td>
<td>0.0000</td>
<td>0.5000</td>
<td>I</td>
<td>II 0.6 ▼</td>
</tr>
<tr>
<td>Shapingba District</td>
<td>0.3770</td>
<td>0.3641</td>
<td>0.1756</td>
<td>0.0833</td>
<td>0.0000</td>
<td>III</td>
<td>IV 0.3 ▲</td>
</tr>
<tr>
<td>Jiulongpo District</td>
<td>0.0833</td>
<td>0.2167</td>
<td>0.4755</td>
<td>0.2246</td>
<td>0.0000</td>
<td>III</td>
<td>II 0.58 ▲</td>
</tr>
<tr>
<td>Nanan District</td>
<td>0.0710</td>
<td>0.1905</td>
<td>0.5105</td>
<td>0.2280</td>
<td>0.0000</td>
<td>III</td>
<td>II 0.5 ▲</td>
</tr>
<tr>
<td>Beibei District</td>
<td>0.2500</td>
<td>0.2054</td>
<td>0.2807</td>
<td>0.0140</td>
<td>0.2500</td>
<td>II</td>
<td>II 0.65 ▼</td>
</tr>
<tr>
<td>Wansheng District</td>
<td>0.2798</td>
<td>0.1628</td>
<td>0.2641</td>
<td>0.0136</td>
<td>0.2798</td>
<td>I</td>
<td>II 0.5 ▲</td>
</tr>
<tr>
<td>Tongnan District</td>
<td>0.2000</td>
<td>0.2149</td>
<td>0.4621</td>
<td>0.1230</td>
<td>0.0000</td>
<td>III</td>
<td>II 0.65 ▼</td>
</tr>
<tr>
<td></td>
<td>0.2221</td>
<td>0.2167</td>
<td>0.4483</td>
<td>0.1129</td>
<td>0.0000</td>
<td>III</td>
<td>III 0.38 ▲</td>
</tr>
<tr>
<td></td>
<td>0.4250</td>
<td>0.2804</td>
<td>0.1913</td>
<td>0.1033</td>
<td>0.0000</td>
<td>III</td>
<td>III 0.38 ▲</td>
</tr>
<tr>
<td></td>
<td>0.4933</td>
<td>0.2642</td>
<td>0.1603</td>
<td>0.0823</td>
<td>0.0000</td>
<td>IV</td>
<td>IV 0.38 ▲</td>
</tr>
<tr>
<td></td>
<td>0.5000</td>
<td>0.2206</td>
<td>0.0295</td>
<td>0.0000</td>
<td>0.2500</td>
<td>III</td>
<td>III 0.35 ▲</td>
</tr>
<tr>
<td></td>
<td>0.5298</td>
<td>0.1811</td>
<td>0.0242</td>
<td>0.0000</td>
<td>0.2649</td>
<td>I</td>
<td>III 0.35 ▲</td>
</tr>
</tbody>
</table>
Analysis of Evaluation Results

Table 3 shows that by referring to the results of integrated scoring mean evaluation, conformance rate of results achieved by uncertainty measurement evaluation is 82.50% while the conformance rate of that by entropy weight calculation is 65.00%. Reasons for that non-conformance can fall into the following three categories: signal ◆ indicates that the non-conformance arises from breakdown of classifying the regional vulnerability according to Reference 2. For instance, Shapingba District, Dazu County, Kai County and Wulong County are all located at the breakdown line of classification, which causes evaluation results that are fluctuated between two classes. Signal ▲ refers to that the non-conformance takes place when credibility $\lambda = 0.75$. For example, the vulnerability of Nanan District with Level II by equal-weight calculation is 0.75 while the value is 0.7202 by entropy theory, which is a little less than limit $\lambda = 0.75$. There are only two cases in ▼ category, which is resulted from the two reasons mentioned above. Generally speaking, only one level gap is between the two evaluation results by the different weight calculation, which reveals that the uncertainty measurement method adopted here is reliable and reasonable because the result is closer to the actual situation thanks to the fact that this theory includes not only the unpredictable factors but also the objective weights.

CONCLUSIONS

(1) The uncertainty measurement system was modeled to evaluate and classify the vulnerability of regional geological disasters. The major four factors that influence the vulnerabilities of regional geological disasters were selected and consequently, uncertainty measurement functions were determined according to the historic records. Through entropy calculation, each index weight was obtained, which reduced involvement of subjective assumption in process of assessment. In the last stage, classification can be determined according to credibility recognition practice, and consequently, the results about the vulnerabilities of regional geological disasters were achieved. Forty districts and counties in Chongqing City were analyzed by using this measurement model. The findings showed that since the evaluation model took every variable
factor into consideration, the final results were more reliable and reasonable. That proposed a new approach to the vulnerability of regional geological disasters, which was of both theoretical and practical significance.

(2) The vulnerability evaluation of regional geological disasters is based on interaction of several variable factors. As the information retrieval, reference materials and evaluating indexes are incomplete, it is still difficult to comprehensively reflect the overall state of every area. In addition, some factors fail to be involved into the evaluation system because they are hard to collect. The levels of regional vulnerability are only for your information here.

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