Bull Eng Geol Environ (2017) 76:1009–1020
DOI 10.1007/s10064-016-0865-7

ORIGINAL PAPER

# Hazard assessment of potentially dangerous bodies within a cliff based on the Fuzzy-AHP method: a case study of the Mogao Grottoes, China

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Received: 31 October 2015 / Accepted: 25 February 2016 / Published online: 8 March 2016


**Abstract** The Mogao Grottoes are among the most famous sites on the World Heritage list. Several large-scale preservation projects were implemented in 1962, 1982, and 2008, respectively, to improve their preservation conditions. According to field investigation and assessment in recent years, the cliff is stable on the whole because of the reinforcement projects. Among them, there are still 42 potentially dangerous bodies, which may not be stable in some conditions. For the purpose of building the monitoring and early warning system and the long-term preventive preservation of the Mogao Grottoes, an innovative analytical method based on the Analytic Hierarchy Process (AHP) and Fuzzy-AHP was applied to assess the hazard of potentially dangerous bodies within the cliff. Firstly, the hazard was classified into six groups: very high, high, moderate, low, very low, and no hazard, in this study. Secondly, the AHP method was applied to calculate the impact index of each causative factor, and then the hazard assessment of dangerous bodies was made based on statistical analysis. Finally, the Fuzzy-AHP method was applied to calculate the correlation of each factor and determine the comprehensive hazard class. The results indicate that Fuzzy-AHP seems to be more accurate than AHP in hazard assessment. Meanwhile, there is a very high risk body that can threaten 10 caves, three high risk bodies that can threaten 13 caves, and 15 moderate risk bodies can threaten 69 caves in total, while the remaining bodies are defined as low or very low grades. Overall, the results of this study provide much data and a theoretical model in the construction of a monitoring and early warning system currently. Furthermore, the new numerical simulation method also holds the potential application to assess the hazards of other types of heritage sites.

**Keywords** Mogao Grottoes · Potentially dangerous body · Hazard assessment · Fuzzy · AHP

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## Introduction

The Mogao Grottoes were excavated on the cliff of the Mingsha Mountain along the Silk Road, in Gansu Province of China. The cliff has caves and stretches about 1.6 km from north to south, including five floors from the bottom to the top. The history of the Mogao Grottoes dates back 1600 years. So far, 750 caves with 45,000 $m^2$ of wall paintings and 2415 painted sculptures have been discovered (Guo et al. 2009). The Mogao Grottoes were listed as a World Cultural Heritage Site by UNESCO in 1987 because of its extremely high artistic and cultural value. The surrounding rock of the Mogao Grottoes is mainly composed of Quaternary conglomerate, which is defined as weak calcareous cementation with poor resistance to weathering (Li 2002). Therefore, deterioration is one of the most serious problems affecting the long-term preservation of the grottoes. To protect the Mogao Grottoes, large-scale grotto cliff reinforcement projects were implemented in 1962, 1982, and 2008, respectively. These conservation works have had a positive effect based on decades of monitoring data (Zhang et al. 2009). According to the field investigations and assessment in recent years, the cliff of the Mogao Grottoes is stable on the whole, but there are still some potentially dangerous bodies, which may be not stable in some conditions and threaten the preservation of historical relics and the safety of visitors. Therefore, a scientific and comprehensive hazard assessment method is urgently needed.

In order to reduce the threats caused by these defects, a systematic study of the cliff, including engineering properties and potential hazard mapping should be carried out. Because of the relationship between the cliff and slope, a landslide study method is introduced. Varnes (1984) presented the authoritative definition of zonation, which was used as division of the land surface into areas, and ranked these areas according to the degree of actual or potential risk from landslides or other mass movement on the slopes. The main factors influencing a landslide were discussed in his study as well. Meanwhile, Brabb (1984) introduced the term "landslide susceptibility", which means a possibility of occurrence of a landslide based on a set of geo-environmental factors. Both definitions have been widely used in landslide hazard study (Anbalagan 1992; Carrara et al. 1995; Soeters and van Westen 1996; Aleotti and Chowdhury 1999; Guzzetti et al. 1999; Gorsevski et al. 2003; Ayalew et al. 2004; Ayalew and Yamagishi 2005; Akgun et al. 2008, 2012; Kouli et al. 2010; Yalcin et al. 2011; Kayastha et al. 2013; Feizizadeh et al. 2014; Kumar and Anbalagan 2015).

The methods for assessing different landslide risk levels can be divided into three categories: qualitative, semi-quantitative, and quantitative approaches. Qualitative methods depend on expert opinions. The most common types of qualitative methods simply use landslide inventories to identify sites of similar geological and geo-morphological properties that are susceptible to failure (Soeters and van Westen 1996; Aleotti and Chowdhury 1999). Semi-quantitative methods are based on weighing and rating methods, such as the AHP approach, fuzzy logic approach, combined landslide frequency ratio, and fuzzy logic and weighted linear combination (Ercanoglu and Gokceoglu 2004; Kayastha et al. 2013). Quantitative methods are based on numerical expressions of the relationship between controlling factors and landslides (Guzzetti et al. 1999; Demir et al. 2013). It is usually required that methods are clearly understandable, track running stages, and are practical in real application. Another modeling technique evaluated in expert systems is the Analytical Hierarchy Process (AHP) (Saaty 1980), which is widely accepted and applied since it does not require any training stage. It is just based on expert knowledge (Nefeslioglu et al. 2013). Many studies assessing landslide hazard and geo-environmental problems using the AHP method can be found in recent literature (Dai et al. 2001; Ayalew et al. 2004; Ercanoglu et al. 2008; Yalcin et al. 2011; Hasekioğulları and Ercanoglu 2012; Demir et al. 2013; Nefeslioglu et al. 2013). The main advantage of the AHP method is the property given by the statement "depending on expert knowledge"; however, this is also the main disadvantage. Expert subjectivity, particularly in pairwise comparisons, constitutes the main drawback of the AHP (Nefeslioglu et al. 2013). In order to mitigate this subjectivity, the fuzzy logic method has been integrated with AHP, and Fuzzy-AHP models have been constructed to evaluate landslide hazard and geo-environmental problems in recent literature (Leung and Cao 2000; Gorsevski et al. 2006; Akgun et al. 2012; Pourghasemi et al. 2013; Feizizadeh et al. 2014; Feng et al. 2014). Meanwhile, diverse researchers have developed artificial neural network and neuro-fuzzy methods to assess landslide hazard in different areas of the world (Poudyal et al. 2010; Pradhan et al. 2010; Park et al. 2013; Dou et al. 2015). However, research works related to cliff hazard assessment of the Mogao Grottoes are still limited in China.

For constructing a monitoring and early warning system and long-term preventive protection, this study aimed at producing a hazard map of the potentially dangerous bodies within the Mogao Grottoes cliff using AHP and Fuzzy-AHP analytical methods, which are widely accepted, and multi-criteria decision-making approaches. The AHP approach was used to assign weights to both the causative factors and the subcategory of each causative factor. The fuzzy method was applied to calculate the memberships of each factor. Finally, the hazard of each potential dangerous body was determined by Fuzzy-AHP method.

## Study area and assessment layers

### Study area

The study area was the end of the Hexi corridor, along the Silk Road, in Gansu Province of China (Fig. 1), which consists of the southern and northern areas. The southern area is open for visitors because it has been well preserved with high artistic and cultural value. For the long-term preservation and safety protection of visitors and staff, the

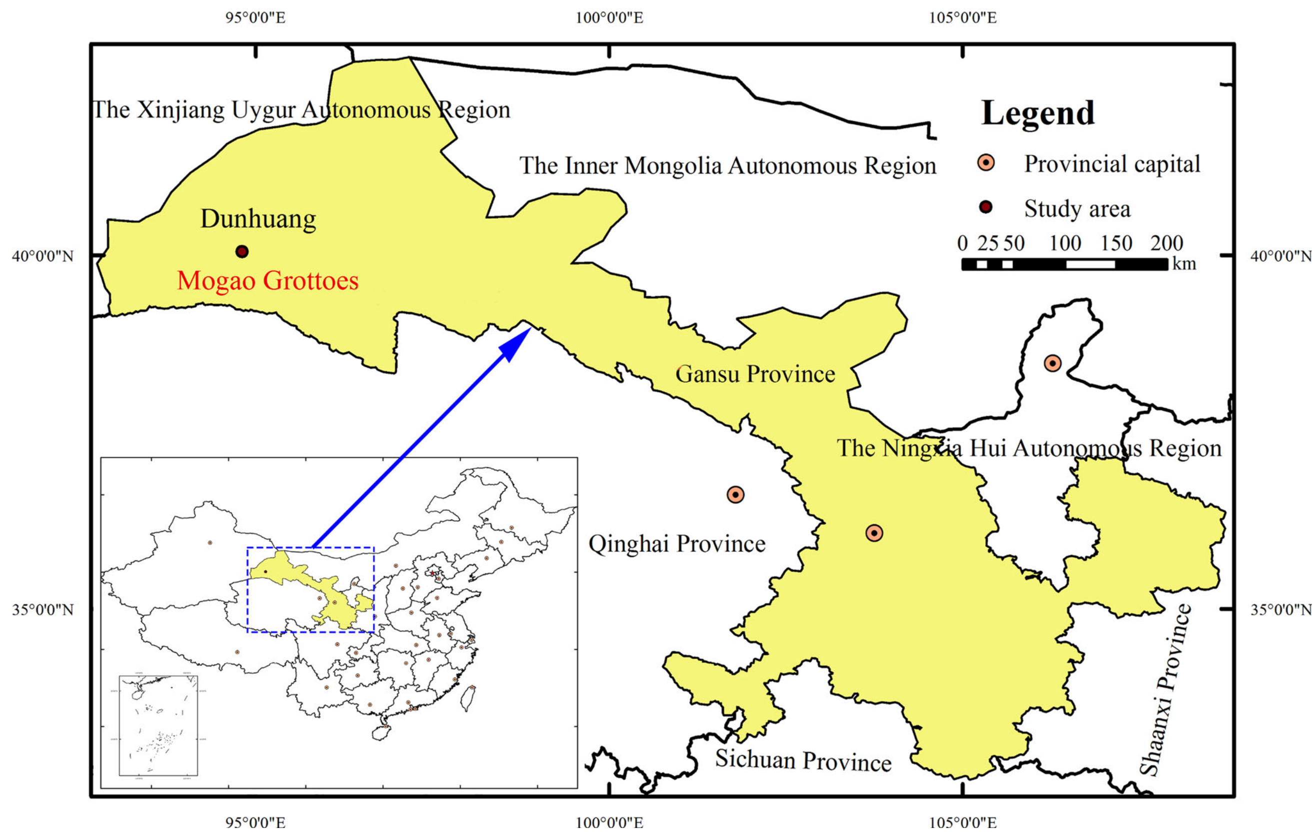


**Fig. 1** Location map of the study area, in the northwest of China along the Silk Road


**Fig. 2** A wide view of three-dimensional digital sign image map of study area

southern area (Fig. 2) was finally chosen as the research area in this study.

## Assessment layers

The first step in the landslide hazard assessment study is collecting information and data of the study area to build assessment layers. For landslide hazard assessment, several spatial parameters control the landslide occurrence, which are important for a specific area, but might not be important for another one (Demir et al. 2013). Therefore, the selection of the cliff hazard assessment layers should be based on a large number of field investigations. Seven possible causative factors, in terms of lithology, cliff shape, dangerous body, fissure, gully, earthquake, and rainfall, were taken into account for the hazard assessment based on the field investigation; meanwhile, each causative factor could be divided into subcategories.

### *Lithology*

Landslide occurrence is closely related to the lithology and weathering properties of the surrounding rocks (Kouli et al. 2010). The field investigation illustrates that caves of the Mogao Grottoes are distributed in the mid-Pleistocene series (Jiuquan group, $Q_2$) and the upper Pleistocene series (Gobi group, $Q_3$). The Jiuquan group ($Q_2$) can be divided further into four engineering geological rock groups from the upper part to the lower one (Wang et al. 2000).

*Cliff shape*

The different cliff sections have different shapes which can certainly influence the cliff stability. According to its shapes, the different cliff sections are mainly divided into step type, vertical type, and cantilevered type (Fig. 3).

*Dangerous body*

The cliff of the Mogao Grottoes is stable on the whole; however, there are some potentially dangerous bodies that are cantilevered on cliff. For the description of these potentially dangerous bodies (Fig. 4), the depth, area, and volume are taken into account.

*Fissure*

There are many fissures within the cliff, which pose a great influence on the stability of the cliff and caves. All the fissures can be divided into three categories based on cause of formation, namely tectonic fissure, unloading fissure, and longitudinal fissure (Fig. 5). These fissures cut the cliff into dangerous bodies, or increase the potential of a body to become more dangerous. Thus, the basic parameters of the fissure, such as the fissure length, width, and the angle between the fissure and cliff face, are mainly applied in fissure description.

*Gully*

The field investigation indicates that there are some gullies that can widen, deepen existing fissures, and accelerate the instability of the cliff. Therefore, a gully should be considered a causative factor, and the length, width, and depth are mainly applied for gully description (Fig. 6).

*Earthquake and rainfall*

Earthquakes and rainfall are selected as causative factors in hazard assessment because they are the main triggers of a landslide (Pradhan et al. 2010). However, the different

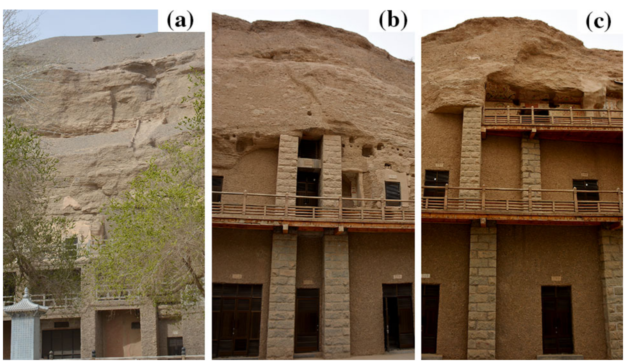


**Fig. 3** Three types of cliff shape: **a** step type; **b** vertical type; and **c** cantilevered type

**Fig. 4** Potentially dangerous body on the cliff. The *dotted line* indicates the area on the cliff with potential risks

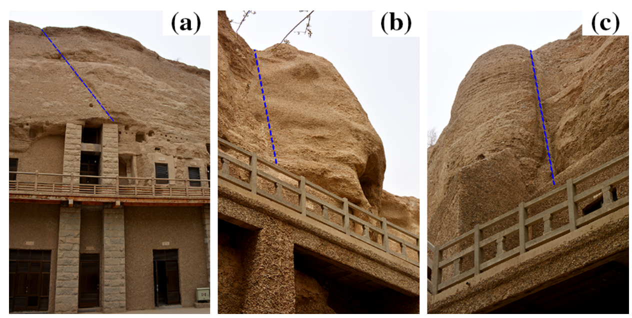


**Fig. 5** Three typical fissure types on the cliff: **a** tectonic fissure; **b** unloading fissure; and **c** longitudinal fissure

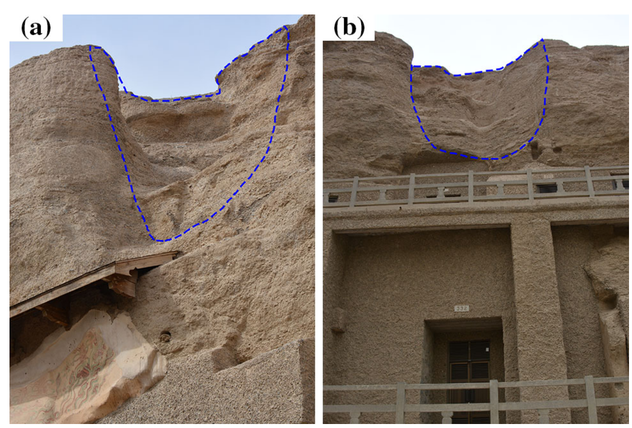


**Fig. 6** Gullies appearing in parts of the cliff: **a** gully on *top* of No. 205 cave, and **b** gully on *top* of No. 332 cave

influence of seismic energy caused by an earthquake or the impact induced by rainfall can be neglected in a small area. For example, in the research area, the earthquake intensity is 7° (Chinese Code for seismic design of building, GB 50011-2010), and the rainfall is low. Therefore, the effect of earthquakes and rainfall in the study area can be considered uniform. Actually, "earthquake" is the most influential factor to threaten the stability of the cliff. However, the study area is not a seismically active region (Shi et al. 2000). Meanwhile, taking into account the fortuitous and unpredictability, the influence of the "earthquake" factor has been reduced artificially.

## Methodology

The fuzzy-AHP comprehensive evaluation method was refined into three steps, and their detailed explanation is given below (Feng et al. 2014).

### Determination of an assessment index system

The first step was to build an index system and identify the indices. The index system included three layers. The topmost layer of the index system was the goal of the assessment, called the goal layer. The second layer of the index system was the selected causative factors, which were reliable, could be effectively collected, and had a significant impact on the target layer, called the criterion layer. The third layer of the index system, which explained the concrete meaning of the second layer, is called index layer. Figure 7 shows the assessment index system of this study according to field investigation.

### Obtaining the weights of indices using AHP

AHP was developed by Thomas L. Saaty in the 1970s based on mathematics and has been widely studied and applied since then. It is a semi-quantitative and multi-criteria decision-making method in which decisions are made using weights through pairwise relative comparisons without inconsistencies in the decision process (Saaty 1980). The primary disadvantage of this approach is that subjective preference in the ranking of factors may differ from one expert to another. Therefore, opinions provided by a large number of experts should be taken into account in the ranking of factors.

The AHP method includes three steps (Saaty 1980; Ma et al. 2013):

Step 1. Divide the complex problem into a hierarchy of factors.

Step 2. Determine the relative importance of different causative factors with respect to the objective: according to a nine-point ordinal scale (Table 1), pairwise comparisons between

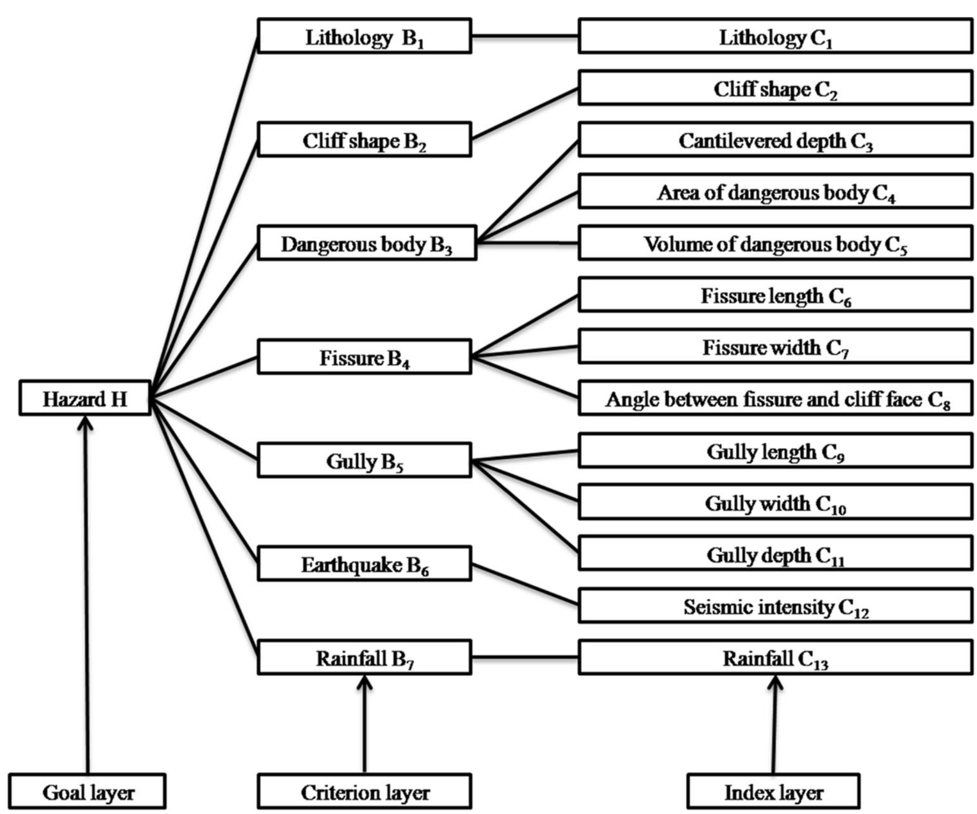


**Fig. 7** The hierarchy structure for hazard assessment

**Table 1** Fundamental scale for pairwise comparisons suggested by Saaty

| Intensity of importance | Definition |
|---|---|
| 1 | Equal importance, two activities contribute equally to the object |
| 3 | Moderate importance, slightly favors one over another |
| 5 | Essential or strong importance, strongly favors one over another |
| 7 | Demonstrated importance, dominance of the demonstrated importance in practice |
| 9 | Extreme importance, evidence favoring one over another of highest possible order of affirmation |
| 2, 4, 6, 8 | Intermediate values, when compromise is needed |
| Reciprocal (i.e. 1/9) | If the comparison was reversed |

**Table 2** RI values for the pairwise comparisons in AHP analysis

| Value of $N$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0.52 | 0.89 | 1.12 | 1.26 | 1.36 | 1.41 | 1.46 | 1.49 | 1.52 | 1.54 | 1.56 | 1.58 | 1.59 |

the various factors are extracted to construct a weight decision matrix $A = (a_{ij})$. The term $a_{ij}$ was governed by the following rules: $a_{ij} > 0; a_{ij} = 1/1a_{ji}(i \neq j); a_{ij} = 1(i,j = 1,2,\ldots,n)$

The weight of an index was calculated using the importance scales in the second and third layers. For this process, the square-root method given by Eq. 1 was used:

$$M_i = \prod_{j=1}^{n} a_{ij}$$
$$\overline{W}_i = \sqrt[n]{M_i}(i = 1,2,\ldots,n) \tag{1}$$
$$W_i = \overline{W}_i \Big/ \sum_{j=1}^{n} \overline{W}_i$$

Step 3. Ensure that each pairwise comparison is consistent with the other comparisons. The ratio of inconsistency can be evaluated by the parameter CR which could be calculated by Eqs. 2, 3, and 4:

$$CR = \frac{CI}{RI} \tag{2}$$

$$CI = \frac{\lambda_{\max} - N}{N - 1} \tag{3}$$

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{W_i} \tag{4}$$

where $\lambda_{\max}$ is the maximum eigenvalue of matrix $A$; N is the total number of causative factors; and RI is a random index. The reference values of RI for different N are shown in Table 2. If CR <0.10, then the comparison satisfies the consistency requirements. Otherwise, an unacceptable inconsistency may exist and AHP cannot produce reasonable results.

AHP is designed as a simple hierarchy structure with two levels in this paper. Table 3 shows the pairwise comparison matrix for causative factors and for the subcategories within each factor. The matrix is structured by three experts who are well acquainted with the Mogao Grottoes. The normalized principal eigenvectors of each matrix, given in the last column of Table 3, indicate the importance of a factor.

## Calculating the relative membership using the fuzzy method

The fuzzy relation concept defined by Zadeh (1973) was used in this study. In general, fuzzy relation theory can be considered fuzzy set theory, which is an extension of ordinary set theory. In ordinary set theory, an element belongs or does not belong to a set that contains only 0 and 1 values. In fuzzy set theory, membership of elements has varying degrees belong to interval [0, 1]. Thus, a fuzzy set can be explained as a set containing elements that have varying degrees of membership in the set (Ercanoglu and Gokceoglu 2004).

The fuzzy method includes three steps (Feng et al. 2014; Peng et al. 2014).

Step 1: Determination of the evaluation criteria

The criteria are assumed as:

$$V = \{v_1, v_2, \ldots, v_n\}\ (n = 1,2,\ldots,\text{the number of classes}) \tag{5}$$

The evaluation criteria employed in this study were determined according to expert consultation. There are six classes in the method: very high (VH), high (H), moderate

**Table 3** Pairwise comparison matrix, factor weights and consistency ratio of the data layers

| Causative factors and subcategories within each factors | Pairwise comparison matrix | | | | | | | Weights |
|---|---|---|---|---|---|---|---|---|
| | [1] | [2] | [3] | [4] | [5] | [6] | [7] | |
| Causative factors | | | | | | | | |
| [1] Lithology ($B_1$) | 1 | | | | | | | 0.166 |
| [2] Cliff shape ($B_2$) | 2 | 1 | | | | | | 0.203 |
| [3] Dangerous body ($B_3$) | 2 | 2 | 1 | | | | | 0.302 |
| [4] Fissure ($B_4$) | 1/2 | 1/2 | 1/3 | 1 | | | | 0.115 |
| [5] Gully ($B_5$) | 1/3 | 1/3 | 1/4 | 1/2 | 1 | | | 0.054 |
| [6] Earthquake ($B_6$) | 1/2 | 1/2 | 1/3 | 1/2 | 2 | 1 | | 0.094 |
| [7] Rainfall ($B_7$) | 1/3 | 1/3 | 1/4 | 1/2 | 2 | 1/2 | 1 | 0.066 |
| Consistency ratio: $0.024 < 0.1$ | | | | | | | | |
| Subcategories within each causative factor | | | | | | | | |
| Dangerous body ($B_3$) | | | | | | | | |
| [1] Cantilevered depth ($C_3$) | 1 | | | | | | | 0.540 |
| [2] Area of dangerous body ($C_4$) | 1/3 | 1 | | | | | | 0.163 |
| [3] Volume of dangerous body ($C_5$) | 1/2 | 1/2 | 1 | | | | | 0.297 |
| Consistency ratio: $0.009 < 0.1$ | | | | | | | | |
| Fissure ($B_4$) | | | | | | | | |
| [1] Fissure length ($C_6$) | 1 | | | | | | | 0.163 |
| [2] Fissure width ($C_7$) | 2 | 1 | | | | | | 0.297 |
| [3] Angle between fissure and cliff face ($C_8$) | 3 | 2 | 1 | | | | | 0.540 |
| Consistency ratio: $0.009 < 0.1$ | | | | | | | | |
| Gully ($B_5$) | | | | | | | | |
| [1] Gully length ($C_9$) | 1 | | | | | | | 0.297 |
| [2] Gully width ($C_{10}$) | 1/2 | 1 | | | | | | 0.163 |
| [3] Gully depth ($C_{11}$) | 2 | 3 | 1 | | | | | 0.540 |
| Consistency ratio: $0.009 < 0.1$ | | | | | | | | |

(M), low (L), very low (VL), and no (N), and the corresponding scores are:

$$\left.\begin{aligned} v_1 = [0.6, 1.0], v_2 = [0.5, 0.6), v_3 = [0.4, 0.5) \\ v_4 = [0.3, 0.4], v_5 = [0.2, 0.3), v_6 = [0, 0.2) \end{aligned}\right\} \quad (6)$$

Step 2: Determination of the fuzzy relationship matrix

The fuzzy relationship matrix is ascertained as:

$$R = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_m \end{bmatrix} = \begin{bmatrix} \mathrm{r}_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \quad (7)$$

where $R$ indicates the membership of the $i$th index belonging to the $j$th rank; $m$ is the number of factor within criterion layer, $n$ is the number of class. In this study, $m = 7$, $n = 6$.

The membership function is established according to the characteristics of the index system. When causative factor is positively correlated with values of these indices, the triangular membership function (Feizizadeh et al. 2014) (Fig. 8) is selected to structure the fuzzy set, which is shown in Eq. 8.

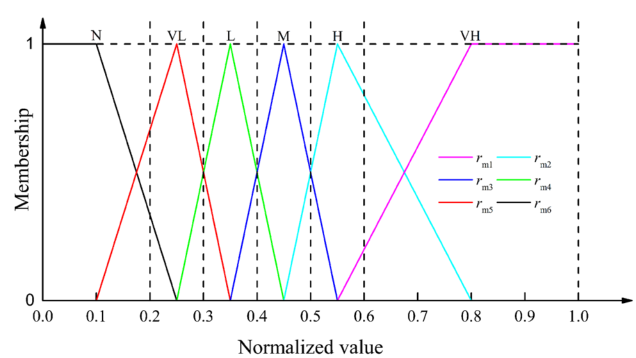


**Fig. 8** The triangular fuzzy membership function (Feizizadeh et al. 2014)

$$
\left.
\begin{array}{l}
r_{m1} = \begin{cases} 1 & x \geq 0.8 \\ \dfrac{x - 0.55}{0.25} & 0.55 < x < 0.8 \\ 0 & x < 0.55 \end{cases} \\
r_{m2} = \begin{cases} 0 & x \geq 0.8 \\ \dfrac{0.8 - x}{0.25} & 0.55 \leq x < 0.8 \\ \dfrac{x - 0.45}{0.1} & 0.45 \leq x < 0.55 \\ 0 & x < 0.45 \end{cases} \\
r_{m3} = \begin{cases} 0 & x \geq 0.55 \\ \dfrac{0.55 - x}{0.1} & 0.45 \leq x < 0.55 \\ \dfrac{x - 0.35}{0.1} & 0.35 \leq x < 0.45 \\ 0 & x < 0.35 \end{cases} \\
r_{m4} = \begin{cases} 0 & x \geq 0.45 \\ \dfrac{0.45 - x}{0.1} & 0.35 \leq x < 0.45 \\ \dfrac{x - 0.25}{0.1} & 0.25 \leq x < 0.35 \\ 0 & x < 0.25 \end{cases} \\
r_{m5} = \begin{cases} 0 & x \geq 0.35 \\ \dfrac{0.35 - x}{0.1} & 0.25 \leq x < 0.35 \\ \dfrac{x - 0.1}{0.15} & 0.1 \leq x < 0.25 \\ 0 & x < 0.1 \end{cases} \\
r_{m6} = \begin{cases} 1 & x < 0.1 \\ \dfrac{0.25 - x}{0.15} & 0.1 \leq x < 0.25 \\ 0 & x \geq 0.25 \end{cases}
\end{array}
\right\} \tag{8}
$$

where $x$ is the normalized value of each causative factor.

Step 3: Determination of comprehensive evaluation class

By performing the fuzzy composite operation between the set of fuzzy weights and the fuzzy relationship matrix, a comprehensive evaluation vector $B_i$ of the index layer is established by Eq. 9, the evaluation matrix $B$ of the criterion layer is established by Eq. 10, and the comprehensive evaluation vector $T$ of the goal layer is established by Eq. 11.

$$B_i = W_{1i} \times R_i \tag{9}$$

$$B = [B_1 \quad B_2 \quad \cdots \quad B_m]^T \tag{10}$$

$$T = W_{2i} \times B \tag{11}$$

where $W_{1i}$ is the weight of factor within index layer; $W_{2i}$ is the weight of factor within criterion layer; $m$ is the number of factor within criterion layer.

The final comprehensive hazard assessment score $K$ is calculated by the weighted mean method (Eq. 12). Thus, based on the above evaluation criteria, when $0 \leq K < 0.2$, the hazard is no; when $0.2 \leq K < 0.3$, the hazard is very low; when $0.3 \leq K < 0.4$, the hazard is low; when $0.4 \leq K < 0.5$, the hazard is moderate; when $0.5 \leq K < 0.6$, the hazard is high; when $0.6 \leq K \leq 1.0$, the hazard is very high.

$$K = T \times S^T \tag{12}$$

where $S = [0.8, 0.55, 0.45, 0.35, 0.25, 0.1]$, which is the mid-score of each class.

## Hazard assessment

### Assessment zone division

On the basis of field investigation and engineering geological analysis, 42 potentially dangerous bodies are picked out, and each body is taken account of in each assessment zone (Fig. 9).

### Data acquisition

Data and information for the assessment index system were measured according to field investigation. The qualitative data, such as lithology and cliff shape, were converted into quantitative values according to expert opinion. Meanwhile, the original measured data were normalized (Eq. 13) because the linear combination is easier.

$$F_i^* = \frac{F_i - F_{\min}}{F_{\max} - F_{\min}} \tag{13}$$

where $F_i^*$ which is equal to $x$ in Eq. 8, is the normalized value of causative factor $F_i$, $F_{min}$ is the minimum value of causative factor $F_i$ in all assessment zones, $F_{max}$ is the maximum value of causative factor $F_i$ in all assessment zones.

### Hazard assessment using AHP

Using the weights calculated by AHP, the final hazard score (Fig. 10) within a zone is given by weighted linear combination according to Eq. 14 (Ayalew et al. 2004; Kayastha et al. 2013).

$$H = \sum_{i=1}^{n} W_i F_i^* \tag{14}$$

where $F_i^*$ is the normalized value of causative factor $F_i$, $W_i$ is the weight of causative factor $F_i$, and $n$ is the number of causative factors.


**Fig. 9** An overview of assessment zones with labels on each cave

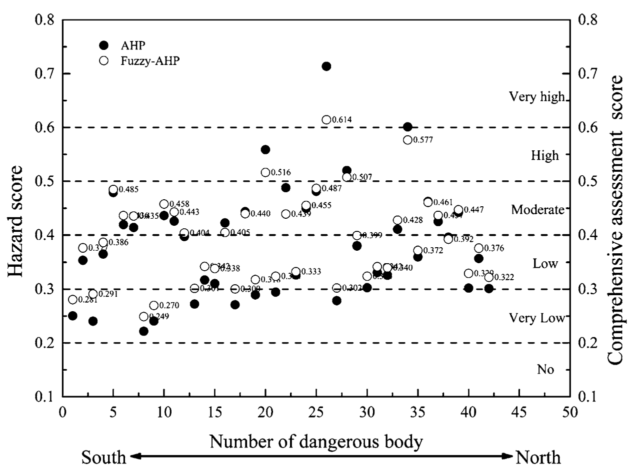


**Fig. 10** Hazard scores calculated by AHP and Fuzzy-AHP

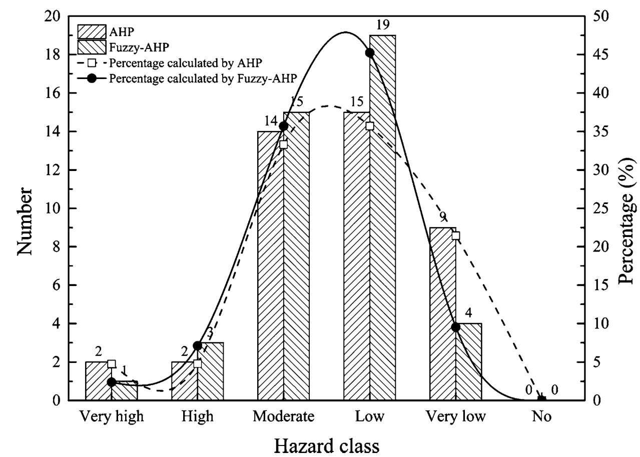


**Fig. 11** Statistics of hazard assessed by AHP and Fuzzy-AHP

## Hazard assessment using Fuzzy-AHP

The comprehensive assessment scores of each assessment zone was calculated by using Fuzzy-AHP, introduced above, and are shown in Fig. 10.

The resulting *H*-scores (hazard scores) calculated by AHP vary from 0.222 to 0.714, while the comprehensive hazard assessment scores calculated by Fuzzy-AHP vary from 0.249 to 0.614. The difference of hazard value calculated by two method types increase when the hazard value is closer to the maximum or minimum, while the difference between them is generally small. The reason for this phenomenon is that the original minimum value of the causative factor can be turned into 0 and the maximum value can be turned into 1 in the normalizing process. Finally, the *H*-score is calculated simply by weighted linear combination. In the AHP method, the causative factor belongs or does not belong to a class set containing only 0 and 1 values as membership. However, in the Fuzzy-AHP method, membership of the causative factor has varying degrees belong to the [0,1] interval. Thus, the Fuzzy-AHP method can be explained as a set containing causative factors that have varying degrees of membership in the set (Ercanoglu and Gokceoglu 2004). For example, the normalized value of one causative factor is 0.6, whose membership belonging to VH class is 1 in the AHP method, while in the Fuzzy-AHP method, the membership belonging to VH class is 0.2 and the membership belonging to H class is 0.8. This is the main difference between the Fuzzy-AHP and AHP methods. Therefore, the minimum *H*-score calculated by AHP will be less than the minimum *H*-score calculated by Fuzzy-AHP, and the maximum *H*-score calculated by AHP will be greater than the maximum *H*-score calculated by Fuzzy-AHP.

The statistics of the hazard assessed by AHP and Fuzzy-AHP are shown in Fig. 11. When the *H*-score was

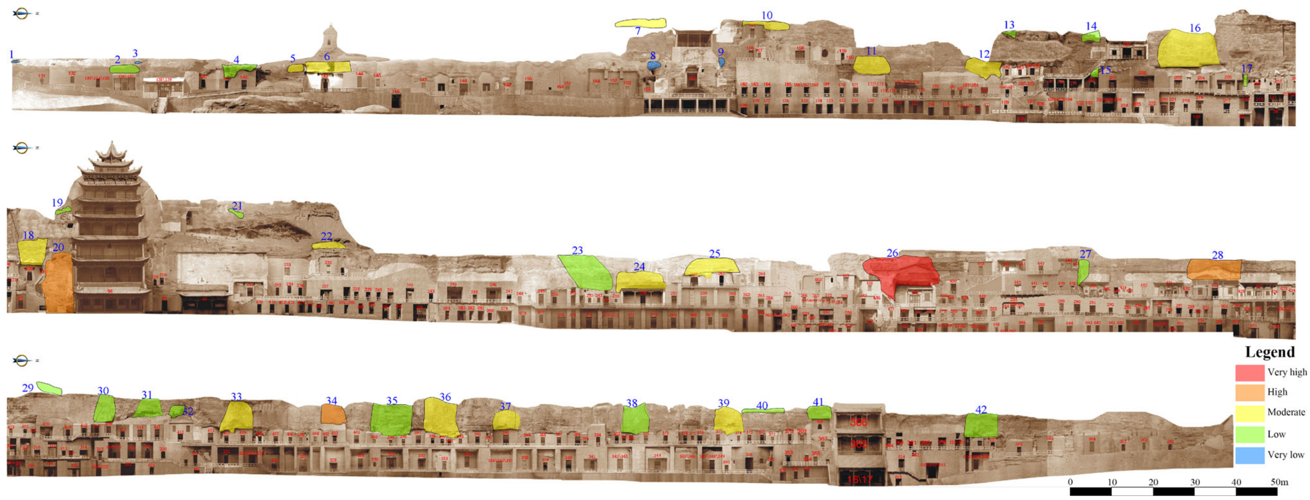


**Fig. 12** Hazard map of potentially dangerous bodies within cliff

**Table 4** Statistics of caves threatened by dangerous bodies

| Hazard class | Number of dangerous bodies | Percentage of dangerous bodies (%) | Number of caves | Percentage of caves (%) |
|---|---|---|---|---|
| Very high | 1 | 2.4 | 10 | 2.0 |
| High | 3 | 7.1 | 13 | 2.6 |
| Moderate | 15 | 35.7 | 69 | 14.0 |
| Low | 19 | 45.3 | 61 | 12.1 |
| Very low | 4 | 9.5 | 3 | 0.6 |
| Total | 42 | 100 | 156 | 31.7 |

calculated by AHP, there were two very high hazard bodies, two high hazard bodies, 14 moderate hazard bodies, 15 low hazard bodies, and nine very low hazard bodies. While the *H*-score was calculated by Fuzzy-AHP, there was one very high hazard body, three high hazard bodies, 15 moderate hazard bodies, 19 low hazard bodies, and four very low hazard bodies. The main difference between the two methods is the number of very high and high hazard bodies. Considering the advantage and disadvantage of Fuzzy-AHP and AHP methods, the *H*-score calculated by Fuzzy-AHP was used as final result.

The result, *H*-map (hazard map), is shown in Fig. 12, in which the *H*-map shows that the safe areas are mainly distributed in both sides of the southern area, while the relatively susceptible zones are mainly concentrated in the middle areas. The statistics of caves threatened by potentially dangerous bodies in different hazard class are shown in Table 4. The result indicates that the very high hazard zones, which cover 2.4 % of dangerous bodies, threaten about 2.0 % of the total investigated caves in the southern area; the high hazard zones, which cover 7.1 % of the bodies, threaten about 2.6 % of the total investigated caves; the moderate hazard zones, which cover 35.7 % of the bodies, threaten a large number of caves, about 14.0 % of the total investigated; the low hazard zones cover about 45.2 % of the bodies; while the very low hazard zones cover about 9.5 % of the bodies. However, 5 % of the caves are threatened by very high and high hazard zones. These caves need more daily maintenance and management.

## Discussion and conclusions

The AHP method is an accurate and applicable method for creating weighted measures in cliff hazard assessment of Mogao Grottoes because of the pairwise relative comparisons of the causative factors without inconsistencies in the decision process (Kayastha et al. 2013). However, this analytic method also has its shortcomings. Nefeslioglu et al. reported problems in the uncertainties raised by the experts constituting the main drawback of the conventional AHP (Nefeslioglu et al. 2013). Therefore, the assessment results calculated merely according to the results obtained by AHP are not authentic due to this defect. In order to mitigate this subjectivity, fuzzy comprehensive assessment is applied to assess the hazard of potentially dangerous bodies within the cliff of the Mogao Grottoes. Based on the authenticity of fuzzy set theory, which is closer to the real conditions, the hazard level assessed by the Fuzzy-AHP method is chosen as the final result since the method is more comprehensive and systematic.

In this study, seven causative factors and 13 subcategories were considered for hazard assessment. The selection of these factors was based on the large-scale field investigation and availability of data for the study area. The most important principle is that the selected factors must have a directly related impact on the cliff hazards. In these causative factors, the impact of a "dangerous body" is the strongest, the "cliff shape" is secondary, the lithology is third, and other factors are "fissure", "earthquake", "rainfall", and "gully" ranked from great influence to small. Actually, "earthquake" is the most influential factor to threaten the stability of cliff. However, the study area is not a seismically active region (Shi et al. 2000). Meanwhile, taking into account the extremely low frequency and unpredictability, the influence of the "earthquake" factor has been reduced artificially to obtain an objective evaluation. Moreover, more factors can be considered on the basis of availability of data for further study.

The assessment results indicate that there is one very high hazard body threatening about 2.0 % of the total investigated caves in the southern area, three high hazard bodies threatening about 2.6 % of the total investigated caves, and 15 moderate hazard bodies, while the remaining bodies are of low and very low hazard. Meanwhile, the assessment results show that the safe areas are mainly distributed on both sides of the southern area because there is only a few dangerous bodies, which are small and not cut by fissure and gully within the low cliff, while the relatively susceptible zones are mainly concentrated in the middle areas where there are 4 or 5 tier caves and many big dangerous bodies within the high cantilevered cliff. There is a dangerous body that is cantilevered and has been cut by many fissures and gullies. The assessment results are consistent with the results of field investigation. This indicates that choosing these causative factors is reasonable, and the Fuzzy-AHP method can be chosen as a new technique to assess the hazard of other cultural heritage sites like the Mogao Grottoes.

The assessment results can also be used to adjust the visiting route of tourists, and it is necessary and significant for constructing a monitoring and early warning system for the long-term preservation of the Mogao Grottoes. Moreover, the cliff hazard map presented in this study is a good reference for other researchers to study the Mogao Grottoes. They should pay more attention to the very high and high hazard bodies and do some conservation works using the valuable information provided by the map. The results of this study provide a valuable basis for some monitoring work, which can mainly concentrate on the very high and high hazard bodies in the construction of a monitoring and early warning system, in recent years.

Certainly, hazard assessment is the first and basic step for risk assessment of the Mogao Grottoes cliff. Further research to assess hazards and risks of each cave will be carried out and aims to provide a hazard or risk map of caves in future.

**Acknowledgments** This work is supported by the National Twelfth Five-Year Plan Science and Technology Support Program of China (Study on the key technologies of risk monitoring and assessment in Dunhuang Mogao Grottoes, grant No. 2013BAK01B01). We would like to express our gratitude. The results of this work are based on the data collected in Dunhuang Academy and the field investigation is also supported by them. We want to thank all the members who gave us lots of help and cooperation.

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