第 42 卷　第 3 期
2023 年 6 月

中　国　岩　溶
CARSOLOGICA　SINICA

Vol. 42　No. 3
Jun. 2023

李 慧, 魏兴萍, 刘 程, 等. 基于变权重–云模型的岩溶隧道涌突水灾害风险评估——以中梁山隧道为例[J]. 中国岩溶, 2023, 42(3): 548-557, 572.
DOI: 10.11932/karst20230306

基于变权重–云模型的岩溶隧道涌突水灾害风险评估——以中梁山隧道为例

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摘　要: 针对岩溶隧道涌突水的致险因素的不确定性、复杂性和隧道涌突水风险评价的主观性, 以成渝中线中梁山岩溶隧道工程为背景, 建立基于正态云模型的隧道涌突水风险评价方法。通过选取地层岩性、地质构造、地表汇水条件、隧道空间位置、地下水循环交替条件作为风险影响因素, 构建涌突水风险评估体系; 基于正态云模型确定的各影响因子数字特征及变权向量计算综合隶属度, 最终判定岩溶隧道涌突水灾害风险等级。结果表明: 成渝中线中梁山隧道涌突水灾害为“II 级”与“V 级”之间, 涌突水灾害发生可能性大且危害高, 与实际开挖结果一致。文章构建的岩溶隧道涌突水灾害风险评估方法, 实现了多元决策下的隧道涌突水灾害风险分级客观性, 适合岩溶隧道的风险评估, 为日后隧道质量控制和寿命评估提供参考。

关键词: 正态云模型; 变权重; 岩溶隧道; 综合隶属度; 涌突水灾害
中图分类号: U456; U458.1　　**文献标识码:** A
文章编号: 1001－4810 (2023) 03－0548－10　　**开放科学(资源服务)标识码(OSID):**

0　引　言

社会经济的快速发展和交通运输需求的激增, 加速了国家高速公路网和铁路网的建设与完善, 促进了隧道工程建设的迅速发展。中国已成为世界上拥有隧道规模最大、数量最多和修建技术最完善的国家[1]。《十四五现代综合交通运输体系发展规划的通知》提出“打造成渝地区双城经济圈一小时交通网, 积极构建成渝城际交通网”的发展规划。推进西南地区深长隧道建设成为建设交通强国、巩固西南地区脱贫攻坚成果的必然要求。西南地区独特的地质环境和岩溶作用形成了地表、地下双层空间结构, 岩溶含水层发达的裂隙、管网、溶洞、溶孔和暗河水系等地下水系统, 成为地表水与地下水交换输移的通道[2], 地表水经常漏失为地下水[3]。复杂的地质结构给隧道施工造成巨大困难, 丰富的地下水系统使隧道施工极易发生涌、突水等严重地质灾害[4], 可能造成巨大的经济损失, 甚至人员伤亡[5]。因此, 对岩溶隧道涌突水灾害风险性的准确评估, 对规避隧道涌突水灾害发生, 保证隧道建设与运营安全具有重要意义。

近年来, 模糊数学[6-7]、层次分析法[8]、BP-神经网

基金项目: 重庆市自然科学基金项目 (cstc2021jcyj-msxmX0616); 国家自然科学基金项目 (42107355, 41202135); 重庆师大学三春湖创新项目 (202201465)

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收稿日期: 2022－01－12

络法[9]、FAHP-TOPSIS 法[10] 和可拓物元理论[11] 等方法被运用到隧道涌突水评估工程实践中，且均取得一定成效，但隧道涌突水影响因素的不确定性、复杂性以及风险评价的主观性等问题尚未解决，评价指标赋权均采用常权理论，对工程施工动态反馈因素研究匮乏，评估结果易存在误差，增大施工风险。李德毅院士基于概率论和模糊数学方法提出的云模型，旨在通过算法解决定性描述向定量数值表达之间的不确定性转换，处理模糊问题方面具备一定优势，在数据挖掘和系统综合评估等方面广泛应用。相比其他评估方法，建立基于云模型理论的岩溶隧道涌水风险评价模型，能清晰直观地反映风险的模糊隶属情况，确定风险等级。变权理论在多属性决策[12]、趋势预测[13]、可靠性分析[14] 等方面应用广泛，能够解决常权理论权重一成不变，与实际情况不符的问题。变权函数和云模型相结合的风险评估，针对岩溶涌突水灾害影响因素的随机性、模糊性和评估结果的主观性具有重要的研究价值和现实意义。

本文基于变权理论与云模型理论针对岩溶隧道涌突水风险评估的优势，以成渝中线中梁山岩溶隧道为研究对象，采用基于正态云模型的岩溶隧道涌突水风险评估方法，引入变权理论动态调整权值，确立涌突水风险等级及划分标准，进行岩溶隧道涌突水灾害风险评估，验证模型的可行性和科学性，以期为相似地理背景的岩溶隧址区的涌突水灾害预测提供参考依据和今后隧道建设的安全施工及运行提供理论参考。

1　变权重-云模型原理

1.1　正态云评估模型

云估模型以模糊理论为基础，通过正向云变换和逆向云变换实现定性概念和定量表示之间的相互映射[15]，反映了各定性概念自身所具有的不确定性，同时揭示了客观事物的随机性和模糊性的关联[16]。云的数字特征反映了定性概念的定量特性，用期望 *Ex*、熵 *En* 和超熵 *He* 三个数值来表征。本文运用正态云模型进行隧道涌突水灾害风险评估，依据正态云模型理论，U 为影响因素的论域且 $U=\{x\}$；假定 T 是 U 上的一个定性概念，随机元素 x 均存在一个具有稳定倾向的随机数值 $\mu(x)\in[0,1]$，即 x 对 T 的隶属度，隶属度在 U 上的分布为云。单个 $(x,\mu(x))$ 结果称为云滴，云滴是论域空间中的一个随机变量，整体服从泛正态分布。对于定性概念 T，正态云模型隶属度满足：

$$\mu_{(x)} = \exp\left(\frac{-^{(x-E_X)2}}{(2En)^2}\right) \tag{1}$$

式中：x 为实际取值；Ex 和 En 为云模型的期望和熵；且 $E'n$ 服从 $En'\sim(En,He^2)$；He 为超熵（即 En 的熵），He 的取值相对于 En 的取值较小，计算 $\mu(x)$ 时，可以用 En 来代替 $E'n$。

1.2　变权重计算与综合隶属度

众多影响因素的综合作用导致岩溶隧道涌突水灾害的发生，影响因素的赋权权值对评估结果准确性至关重要。基于隧道涌突水各影响因子间的相对重要性，引入变权理论，动态调整常数权值。

变权系数综合评估法包含激励型、惩罚型、混合型三种类型[17]，本文采用惩罚型变权函数对评估指标进行处理。

定义 1：$W_j:[0,1]^n\rightarrow[0,1]$，$(x_1,\cdots,x_n)\rightarrow W_j(x_1,\cdots,x_n)$，$j=1,2,\cdots,n$。该映射满足归一性、连续性及单调递减性条件。$W_{(x)}=(W_{1(x)},\cdots,W_{n(x)})$，$(j=1,\cdots,n)$ 为特定状态向量 x 下的变权值。

定义 2：$S:[0,1]^n\rightarrow[0,1],x\rightarrow S_{(x)}=(S_{1(x)},\cdots,S_{n(x)})$。映射 S 为一个 n 维状态变权向量，惩罚性变权向量应满足以下条件：

(1) $x_i\geqslant x_j\rightarrow S_{i(x)}\leqslant S_{j(x)}$；

(2) $S_{i(x)}(i=1,\cdots,n)$ 自变量为连续变量；

(3) 常权向量 W 在满足上述定义前提下有：

$$W_{(x)} = \frac{(W_1S_1(x),\cdots,W_nS_n(x))}{\sum_{j=1}^{n}W_jS_j(x)} = \frac{W\times S(x)}{\sum_{j=1}^{n}W_jS_j(x)} \tag{2}$$

式中：$W\times S(x)$ 为静态权向量 W 和状态变权向量 $S(x)$ 归一化的 Hadamard 乘积；均衡函数 $f(x)$ 计算得状态权向量值[18]。正态云评估模型确定隧道涌突水的单个影响因素隶属度 $\mu_{j(x)}$，结合变权向量 $W(x)$，计算综合隶属度 U，公式为：

$$U = \sum_{j=1}^{n}\mu_j(x)w_j(x) \tag{3}$$

2　岩溶隧道涌突水灾害风险分析

2.1　岩溶隧道涌突水灾害风险评估体系的确立

岩溶涌突水是地下水运移网络或储存条件受外

界干扰造成动力失稳的现象。中梁山岩溶隧址区页岩、灰岩、白云岩等岩层分布，可溶性岩层在地表水和地下水的长期作用下，裂隙、溶洞和暗河等广泛发育。隧道建设过程中穿越岩溶发育的岩层，隧道掘进面底部被质地软弱的填充物填满，给隧道底部的夯实处理造成困难。爆破施工等易导致隧址区岩层内饱水的填充物受到扰动，直接喷涌入施工巷道，威胁施工作业人员的人身安全。

地质构造是涌突水灾害发生的直接因素，严重制约着地下水的水力联系，并影响涌突水灾害发生时的水量补给[19−20]。中梁山隧道属于川东隔挡式构造华蓥山帚状褶皱束之东南缘，位于观音峡背斜两江（长江、嘉陵江）河间地带北段，在强烈侵蚀溶蚀作用下，塑造了典型的“一山三岭两槽”的笔架式地形。构造应力的强烈作用下，促使隧址区形成了溶沟、溶槽和断层破碎带等地质构造，特殊地质构造为地下水的储存提供空间[21]，地下水在高水头压力下易向隧道输送，导致涌突水灾害的发生。

地下水的水位和水量在很大程度上取决于地表的汇水条件[22]，地表水的汇集是隧道涌突水灾害发生的补给条件[23]。降雨量、坡度及渗透系数是影响地表汇水的主要因素。中梁山区的降雨会直接影响地下水的流速、水位等变化[24]；石灰土为主要土壤类型，土层薄且分布不均匀，土壤和岩层渗透性高。中小雨强时，雨滴对地表的击溅能力弱，雨水下渗并沿裂隙形成地下径流[25]，坡面产流主要以地下径流为主；大雨强时，土壤较快达到饱和，下渗能力减弱，地表产流和地下产流并重[26]。地形、坡度决定地表水的汇聚能力[22]，隧址区位于观音峡背斜，西翼岩层倾角为 47°~79°，东翼岩层倾角为 35°~60°，陡峻坡面促进坡面产流，地表径流汇流于低洼地带并渗漏进入地表缝隙和岩溶管道内。

隧道洞身的埋深位置是涌突水灾害发生的重要影响因子。隧道对地下水环境的影响程度由隧道的埋深和其与地下水位的相关关系决定[27]。依据中梁山的地形地貌、地质环境和水域状况，可分为上层水循环带、潜水循环带和深层溶隙水渗透带 3 类地下水循环系统（图 1，图 2）。中梁山岩溶区隧道均位于地下水位以下，存在渗水或涌突水问题。在枯水期，不易发生渗水或涌突水问题；在雨季或丰水期，降雨量丰沛，地表径流大量补给地下水，隧道洞内裂隙的出水量增大甚至会形成新的涌突水点。同时，岩溶裂隙发育程度随深度增加逐渐降低[28]，地下水的水压力也会影响涌突水灾害的发生。

图 1　成渝中线中梁山隧道隧址区位置图

Fig. 1　Location of Zhongliangshan tunnel on the middle route of Chengdu-Chongqing

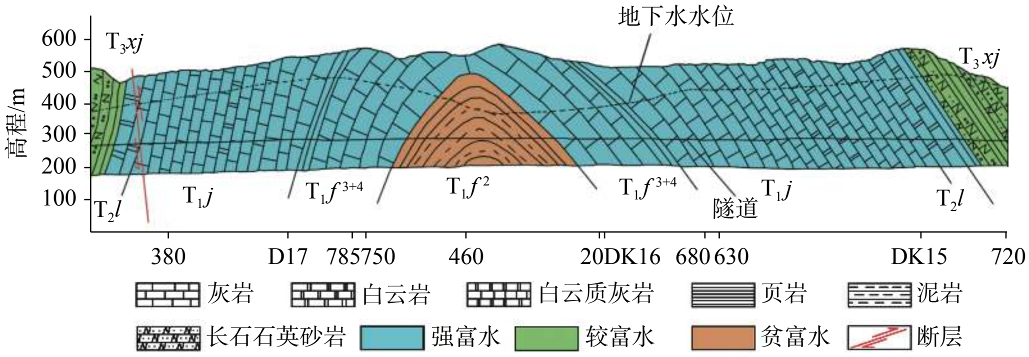

图 2　中梁山岩溶隧道水文地质剖面图

Fig. 2　Hydrogeological profile of Zhongliangshan tunnel

本文岩溶隧道涌突水风险评估考虑以下影响因子（图 3）：① 地层岩性，包括岩层碳酸钙含量和岩石结构；② 地质构造，包括导水断裂构造、阻水断裂构造和褶皱构造；③ 地表汇水条件；④ 隧道空间位置；

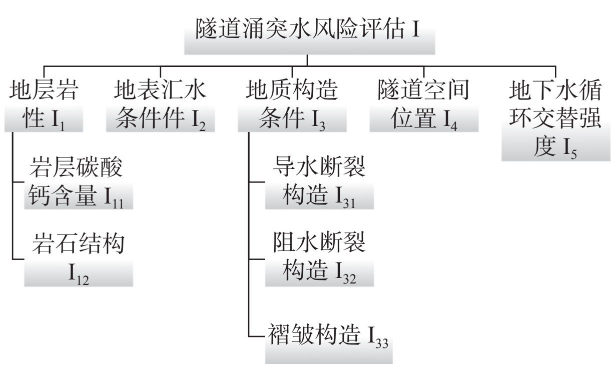

图 3　中梁山岩溶隧道涌突水风险评估指标体系

Fig. 3　Risk assessment index system of water inrush in Zhongliangshan tunnel

⑤ 地下水循环交替条件。

参考武鑫、刘敦文等[6, 29] 的研究方法并向科研高校地质灾害领域教授、隧道施工单位工程师和隧道检测单位工程师共 8 位专家咨询，确定各影响因素对岩溶隧道涌突水灾害等级及分级标准，明确成渝中线中梁山隧道涌突水灾害各影响因素的参数值。隧道涌突水风险等级划分标准及因素取值范围见表 1；岩溶隧道涌突水灾害影响因素基本参数见表 2。

2.2　岩溶隧道涌突水风险评价因素及分级标准

根据隧道涌突水影响因素取值范围，确定各风险等级的正态云模型数字特征，数字特征计算公式[29]如下：

$$\begin{cases} E_x = \dfrac{(C_{max} + C_{min})}{2} \\ E_n = \dfrac{(C_{max} - C_{min})}{6} \\ H_e = K \end{cases} \tag{4}$$

式中：$C_{\max}$ 和 $C_{\min}$ 为隧道涌突水五个风险等级标准区间的边界值；*Ex* 为期望，表示云滴在论域空间分布的期望，即云模型覆盖范围面积的中心；*En* 表示熵，由定性概念的随机性和模糊性共同决定；超熵 *He* 是 *En* 的熵，揭示了模糊性和随机性的关联，反映了云滴的离散程度；*K* 为当前超商取值，根据经验值取 0.01[30]。各风险等级数字特征计算结果见表 3。

如图 4a 至 4d、4f 所示，各单因素云图自左向右风险评价等级逐步提高，表明地层岩性、地表水的汇水条件、导水断裂构造与褶皱构造和岩溶隧道涌突

表 1　岩溶隧道涌突水灾害风险影响因素及分级标准

Table 1　Influencing factors and classification standards of water inrush disaster in karst tunnels

影响因素			无风险(Ⅰ 级)	轻度风险(Ⅱ 级)	中度风险(Ⅲ 级)	高度风险(Ⅳ级)	最高风险(Ⅴ 级)
I	I_1	I_{11}	1~4	4~8	8~12	12~16	16~20
		I_{12}	1~4	4~8	8~12	12~16	16~20
	I_2		1~4	4~7	7~12	12~17	17~20
	I_3	I_{31}	1~6	6~10	10~14	14~17	17~20
		I_{32}	1~4	4~6	6~10	10~14	14~17
		I_{33}	20~16	17~14	14~10	10~4	4~1
	I_4		20~18	18~14	14~8	8~3	3~1
	I_5		20~16	16~12	12~8	8~4	4~1

表 2　岩溶隧道涌突水影响因素正态云模型数字特征

Table 2　Digital characteristics of normal cloud model for influencing factors of water inrush in karst tunnels

影响因素	Ⅰ 级	Ⅱ 级	Ⅲ 级	Ⅳ 级	Ⅴ 级
	（Ex,En,He）	（Ex,En,He）	（Ex,En,He）	（Ex,En,He）	（Ex,En,He）
I_{11}	(2.5,0.5,0.01)	(6,0.66,0.01)	(10,0.66,0.01)	(14,0.66,0.01)	(18,0.66,0.01)
I_{12}	(2.5,0.5,0.01)	(6,0.66,0.01)	(10,0.66,0.01)	(14,0.66,0.01)	(18,0.66,0.01)
I_2	(2.5,0.5,0.01)	(5.5,0.5,0.01)	(9.5,0.83,0.01)	(14.5,0.83,0.01)	(18.5,0.5,0.01)
I_{31}	(3.5,0.83,0.01)	(8,0.66,0.01)	(12,0.66,0.01)	(15.5,0.5,0.01)	(18.5,0.5,0.01)
I_{32}	(3.5,0.5,0.01)	(5,0.33,0.01)	(8,0.66,0.01)	(12,0.66,0.01)	(15.5,0.5,0.01)
I_{33}	(18.5,0.5,0.01)	(15.5,0.5,0.01)	(12,0.66,0.01)	(7,1,0.01)	(2.5,0.5,0.01)
I_4	19,0.33,0.01)	(16,066,0.01)	(11,1,0.01)	(5.5,0.83,0.01)	(2,0.33,0.01)
I_5	(18,0.66,0.01)	(14,0.66,0.01)	(10,0.66,0.01)	(6,0.66,0.01)	(2.5,0.5,0.01)

表 3　岩溶隧道涌突水灾害影响因素基本参数

Table 3　Basic parameters of influencing factors of water inrush disasters in karst tunnels

隧道	DK14+720~ DK15+630	DK15+630~ DK15+680	DK15+680~ DK16+020	DK16+020~ DK16+460	DK16+460~ DK16+750	DK16+750~ DK16+785	DK16+785~ DK17+380
I_{11}	19	5	19	8	18.5	8	18.5
I_{12}	18	15	18	15	18	15	18
I_{2}	18	8	17	12	17	8	17
I_{31}	16	7	18	5	18	7	15
I_{32}	6	2	2	4	2	4	2
I_{33}	6	12	12	8	5	3	14
I_{4}	14	15	13	15	14	12	18
I_{5}	15	15	15	9	17	15	7

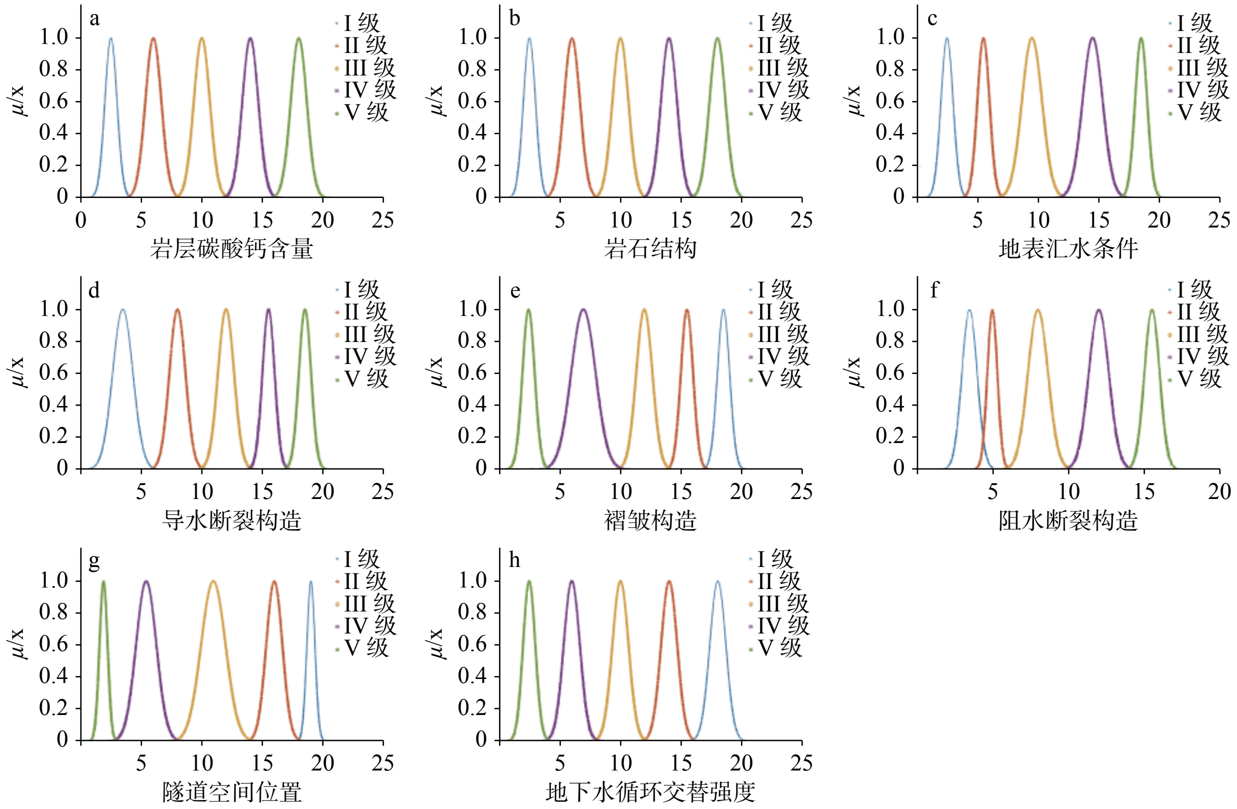

图 4　单影响因子典型云模型

Fig. 4　Normal cloud model with single factor

水风险呈负相关。地表岩溶洼地、槽谷等补给区的汇水面积影响地下水补给量；导水断裂构造和褶皱构造等地质造将地表水体、富水溶腔及地下暗河或高压强含水层与隧道贯通时,加剧了涌突水灾害发生的可能性。图 4e、图 4 g 和 4 h 中单因素云图自左向右安全评价等级逐步降低，地下水循环越快，表明地下储水空间越大，岩溶隧道越容易发生涌突水；阻水断裂构造和隧道位置埋深高于地下水位，隧道受到地下水循环条件及水压的影响越小，则不易发生岩溶隧道涌突水灾害。

如前文所述，该云图表明了单因素影响下岩溶涌突水灾害的风险等级关系，通过惩罚变权理论进行多因素叠加，获得符合实际岩溶隧道涌突水灾害的综合隶属度结果。

3　工程算例

成渝中线中梁山隧址区岩溶强烈发育，隧道工

程在建设时遭遇不同程度的岩溶涌突水问题，并对环境造成了难以恢复的影响。因此，采用本文建立的变权重–云模型进行岩溶隧道涌突水灾害风险评估。岩溶隧道涌突水灾害影响因素基本参数如表 3 列出。

因各影响因素存在量纲差异，为方便计算，将各影响因素的参数值归一化处理，结果见表 4。

3.1　常权及变权计算

岩溶隧道影响因素的变权向量由常权向量和状态变权向量计算确定。因此，首先需要计算各变权向量因素对应的常权向量。本文采用 AHP 法[31]确定岩溶隧道涌突水影响因素的常权向量，判断矩阵为：

$$A=\begin{Bmatrix}1.00 & 0.14 & 4.00 & 0.17 & 1.60 & 0.20 & 0.25 & 0.25\\ 7.00 & 1.00 & 2.00 & 0.40 & 0.48 & 0.50 & 1.67 & 2.22\\ 0.25 & 0.50 & 1.00 & 0.38 & 0.69 & 0.67 & 0.50 & 0.60\\ 6.00 & 2.50 & 1.60 & 1.00 & 1.20 & 2.50 & 0.33 & 0.50\\ 6.00 & 2.20 & 1.45 & 0.83 & 1.00 & 0.67 & 0.40 & 4.00\\ 5.00 & 2.10 & 1.50 & 0.40 & 1.50 & 1.00 & 2.00 & 2.00\\ 4.00 & 0.60 & 2.00 & 3.00 & 2.50 & 0.50 & 1.00 & 1.67\\ 4.00 & 0.45 & 1.67 & 2.00 & 0.25 & 0.50 & 0.60 & 1.00\end{Bmatrix}$$

计算得出常权向量 W：

W=(0.0738,0.1316,0.0590,0.1593,0.1508,0.1618,0.1643, 0.0995)

惩罚型变权、激励型变权以及混合型变权均为状态变权[32]。惩罚型变权强调各因素的均衡性，针对单因素评估值，对低水平评估值的减少反应灵敏，对高水平评估值的增加反应迟缓。故本文采用惩罚性状态变权向量，表示各影响因素在岩溶隧道涌突水灾害发生中的不利影响，判定结果较为保守。n 维指数型状态变权向量 S(x) 中第 i 项可写作[32–33]：

$$S_i(x_1,\cdots,x_n)=f(\beta x_i-\bar{x})=e^{-\alpha(x_i-\beta)} \tag{5}$$

式中：$\bar{x}$为状态向量平均值；$\alpha\geqslant 0$, $0<\beta\leqslant 1$，其中β是否定水平，α为惩罚水平，α的取值越大则惩罚效果越明显[34]。根据表 4 判定，各影响因素的参数值归一化后小于 0.5 的影响因素处于边缘状态，因此，本文选取否定水平β=0.5，惩罚水平$\alpha=0.5$。结合状态变权向量 S(x) 和常权向量 W 计算变权向量 W(x)[32]，结果如下：

$W_1(x)$=(0.0628, 0.1150, 0.0516, 0.1467, 0.1763, 0.1939, 0.1595, 0.0941)

W2(x)=(0.0838, 0.1149, 0.0619, 0.1717, 0.1845, 0.1529, 0.1435, 0.0869)

W3(x)=(0.0632, 0.1158, 0.0533, 0.1402, 0.2012, 0.1667, 0.1649 , 0.0947)

W4(x)=(0.0761, 0.1129, 0.0548, 0.1779, 0.1703, 0.1669, 0.1410, 0.1000)

W5(x)=(0.0625, 0.1129, 0.0520, 0.1367, 0.1962, 0.1955, 0.1566, 0.0877)

W6(x)=(0.0748, 0.1110, 0.0598, 0.1659, 0.1674, 0.1872, 0.1500, 0.0839)

W7(x)=(0.0637, 0.1151, 0.0530, 0.1508, 0.2000, 0.1573, 0.1437, 0.1163)

表 4　岩溶隧道涌突水灾害影响因素参数值归一化结果

Table 4　Normalized parameter values of influencing factors of water inrush disasters in karst tunnels

隧道	DK14+720~DK15+630	DK15+630~DK15+680	DK15+680~DK16+020	DK16+020~DK16+460	DK16+460~DK16+750	DK16+750~DK16+785	DK16+785~DK17+380
I_{11}	0.95	0.21	0.95	0.37	0.92	0.37	0.92
I_{12}	0.89	0.74	0.89	0.74	0.89	0.74	0.89
I_2	0.89	0.37	0.84	0.58	0.84	0.37	0.84
I_{31}	0.79	0.32	0.89	0.21	0.89	0.32	0.74
I_{32}	0.31	0.06	0.06	0.19	0.06	0.19	0.06
I_{33}	0.26	0.58	0.58	0.37	0.21	0.11	0.68
I_4	0.68	0.74	0.63	0.74	0.68	0.58	0.89
I_5	0.74	0.74	0.74	0.42	0.84	0.74	0.32

3.2 涌突水风险灾害评估

各因素对岩溶隧道涌突水灾害的权重由各段岩溶隧道涌水灾害的影响因素组合的变权向量计算得出。依据公式(1)计算不同隧道涌突水影响因素的隶属度，结合不同段岩溶隧道的变权向量，利用公式(3)得出各段岩溶隧道的综合隶属度。

在此基础上，依据最终的综合隶属度，按照最大隶属度原则，确定各段岩溶隧道涌突水的风险灾害的风险等级，涌突水灾害风险等级计算公式为：

$$L = max(\mu_1, \cdots, \mu_n) \tag{6}$$

成渝中线中梁山岩溶隧道涌突水灾害为II 级~V 级(表 5)，中高风险区交替分布，其中 DK15+630~DK15+680、DK16+750~DK16+785 为 II 级，DK16+020~DK16+460 为III 级DK14+720~DK15+630、DK15+680~DK16+020、DK16+460~DK16+750 和DK16+785~DK17+380 为 V 级。岩溶隧道涌突水灾害是多种影响因素共同作用的结果，易发生涌突水灾害的高风险隧道的各影响因子的参数值高于低风险区的影响因子参数值，且四段最高涌水风险区位于可溶岩与非可溶岩接触带，可溶岩地层是孔隙、裂隙与管道 3 重介质系统，空隙率大[21]，岩溶发育，地下水活跃，为涌水灾害的发生提供了条件，增加了涌突水灾害发生的可能性，这与陈紫云[35]针对西南某隧道的研究结论相似，符合实际的隧道涌突水状况。

表 5　岩溶隧道涌突水灾害风险等级综合隶属度级评估结果

Table 5　Assessment of comprehensive membership grades of water inrush disasters in karst tunnels

隧道	DK14+720~DK15+630	DK15+630~DK15+680	DK15+680~DK16+020	DK16+020~DK16+460	DK16+460~DK16+750	DK16+750~DK16+785	DK16+785~DK17+380
I级	0.000 5	0.010 5	0.007 0	0.092 9	0.041 8	0.059 6	0.013 1
II级	0.104 5	0.225 6	0.098 8	0.091 9	0.062 8	0.174 2	0.070 4
III级	0.012 9	0.122 4	0.086 5	0.059 8	0.006 6	0.098 9	0.007 1
Ⅳ级	0.098 6	0.047 4	0.006 8	0.110 4	0.029 6	0.043 5	0.092 1
Ⅴ级	0.147 2	0.000 5	0.154 7	0.000 4	0.172 0	0.058 7	0.125 6
风险等级	Ⅴ级	II级	Ⅴ级	III级	Ⅴ级	II级	Ⅴ级

4 结　论

(1)将变权理论与云模型相结合，应用于岩溶隧道涌突水灾害风险评估，选取地层岩性、地质构造、地表汇水条件、隧道空间位置、地下水循环交替条件作为风险分级影响因素，确定涌突水风险灾害等级及分级标准，制定评价指标体系；

(2) 变权理论构造均衡函数，岩溶隧道各指标依具体情况赋权，规避了指标之间相互中和。量纲一计算得出的变权权重能够观察到同一样本内各指标的变化幅度和相对重要程度。 云模型和变权权重计算的综合隶属度，实现了多元决策下岩溶隧道涌突水灾害风险分级；

(3) 构建岩溶隧道涌突水风险等级评估模型，结合成渝中线中梁山岩溶隧道涌突水灾害进行实例验证。结果表明：重庆中梁山岩溶隧道 DK15+630~DK15+680 和 DK16+750~DK16+785 为轻度风险隧道段，DK16+020~DK16+460 为中度风险段，DK14+720~DK15+630、DK15+680~DK16+020、DK16+460~DK16+750 和 DK16+785~DK17+380 为最高风险段；本文构建的岩溶隧道涌突水灾害风险评价方法可考察不同参数组合下岩溶隧道涌突水风险等级差异并做出定量描述，与实际风险情况基本一致，较传统的层次分析法，对隧道涌突水风险评估更具参照性和客观性，为岩溶隧道隧道涌突水灾害评估提供了一种新方法，能够有效解决岩溶隧道涌突水灾害风险预测的模糊性、随机性和评判的主观性问题。

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Risk assessment of water inrush disasters of karst tunnels based on variable weight-cloud model: A case study of Zhongliangshan tunnel

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Abstract　In order to solve the uncertainty and complexity of risk factors and the subjectivity of risk assessment of water inrush disasters in karst tunnels, the risk of water inrush disaster has been scientifically assessed. According to the Zhongliangshan karst tunnel project on the middle route of Chengdu-Chongqing, the study constructed a risk assessment model of water inrush disasters in karst tunnels based on variable weight-cloud model. First of all, referring to the research methods of Wu Xin, Liu Dunwen and others, and consulting professors in the field of geological disasters and engineers from tunnel construction and inspection units, a total of 8 experts determined the grade and classification standard of each influencing factor on water inrush disasters of karst tunnels, and clarified the parameter value of each influencing factor of Zhongliangshan tunnel on the middle route of Chengdu-Chongqing.

In this study, five influencing factors were selected to construct an index system of risk assessment of the water inrush in karst tunnels. These five factors include formation lithology (calcium carbonate content in strata and rock structure), geologic structures (water-conducting fault structure, water-blocking fault structure and fold structure), surface catchment conditions, tunnel spatial locations and alternating conditions of groundwater circulation. In addition, the grading standards of water inrush disasters were determined, and accordingly the disasters were divided into five risk levels, low, mild, moderate, high and highest.

Firstly, the cloud model was used to determine digital characteristics of the risk level of each index. The diagram of membership cloud of each influencing factor was drawn by MATLAB. The single factor membership degree ($\mu_{j(x)}$) of each influencing factor was calculated according to parameter values of water inrush disasters in karst tunnels. Secondly, the analytic hierarchy process (AHP) was used to determine the constant weight. In order to avoid the situation that the constant weight does not change with the state value of the index to be evaluated, the punitive variable weight method was used to determine the variable weight vector (W(x)) and the comprehensive membership degree (U). Finally, according to the principle of maximum membership degree, risk levels of water inrush disasters in karst tunnels were calculated, and water inrush disaster situations of 7 sections in Zhongliangshan Tunnel on the middle route of Chengdu-Chongqing were determined. The results show that water inrush disasters in Zhongliangshan tunnel are between level III and level VI, with a high risk. Among them, DK15 + 630-DK15 + 680 and DK16 + 750-DK16 + 78 are the sections with a moderate risk; DK16 + 020-DK16 + 460 are of high risk; DK14 + 720-DK15 + 630, DK15 + 680-DK16 + 020, DK16 + 460-DK16 + 750 and DK16 + 785-DK17 + 380 are the sections with a highest risk. Water inrush disasters of karst tunnels can be attributed to a variety of influencing factors. The parameter value of each influencing factor of the high-risk section is higher than that of the low-risk section, and the risk of water inrush disasters in a transition zone between a karst area and a non-karst area is the highest. With the large porosity, the developed karst, and active groundwater, the soluble rock stratum is a three-medium system of pores, fissures and

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several changes in the direction of the surface water system and the repeated scouring and burying of the paleochannel, which has contributed to the complexity of today's paleochannel in terms of its direction, burial depth and stratigraphic structure, over these seven hundred years.

In this paper, the characteristics of changes, erosion, identification, depth and stratigraphic structure of the Xuzhou paleochannel are analyzed through data collection, field exploration, drilling, geophysical exploration and other geological methods, and the influence of alluvium formed by the paleochannel on karst collapse and engineering construction has been studied. It is concluded that since the late Pleistocene, a total of 5 rivers have flowed through Xuzhou. Among them, there are 2 paleochannels in late Pleistocene, both originating in Shandong and entering Xuzhou City from north, and 3 in the Holocene, namely, the ancient Sishui river, the ancient Bianshui river and the ancient Yellow River. Besides, the strata of the Xuzhou paleochannel were firstly formed by the flood of the Bianshui river and the Sishui river, and then by the alluviation of the Yellow River. Therefore, the strata are characterized by "new" (The age is young, mainly formed by the flooding of the Yellow River.), "soft" (Many strata present the large compressibility with high water content), "miscellaneous" (The strata contain bricks, tiles, stones and pottery of the underground ancient city.), "changing" (The large area of cover caused by the flooding of the Yellow River not only buried the ancient city, but also changed the landform). Furthermore, the paleochannel has created favorable geological structure for the formation of karst collapse because the formation of superimposed silt and silt deposits as well as the scouring to the old clay that is steadily distributed formed a replenishment skylight of underlying karst aquifer. This is also the main reason why the collapse points are densely distributed near the paleochannel. Finally, due to the strong water abundance near the paleochannel, the construction of the subway shield is subject to the sand inrush caused by silt and mealy sand. At the same time, the special stratigraphic structure and engineering geological characteristics of the paleochannel will have a great influence on the stability of foundation pit engineering and shallow foundation buildings, and hence corresponding engineering measures should be taken during the project construction.

Key words paleochannel, karst collapse, engineering properties, influence

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pipelines, which provides conditions for the occurrence of water inrush disasters and thus increases disaster possibility.

The assessment result is in consistency with the actual situation of water inrush and tunneling. The consistency indicates that the risk assessment index and its system are applicable to water inrush assessments in karst tunnel areas. The cloud model intuitively reflects a fuzzy membership of risk; the variable weight theory constructs an equilibrium function, and each index is weighted according to the specific situation. It is a good solution to the problem of mutual neutralization between the indexes in the risk assessment of water inrush in karst tunnels, which is conducive to observing the change range and relative importance of each index. The risk assessment method of water inrush disasters of karst tunnels constructed in this paper can realize the objectivity of risk classification of water inrush disasters in tunnels from a multiple decision-making perspective, which is applicable to the risk assessment of karst tunnels and provides reference for the tunnel quality control and life assessment in the future.

Key words normal cloud model, variable weight theory, karst tunnel, comprehensive membership degree, water inrush disaster

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