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岩溶管道与裂隙介质间溶质交换研究进展

罗明明¹, 陈 静¹, 季怀松¹, 万 里¹, 李成根¹, 周 宏²

1. 中国地质大学环境学院, 湖北武汉 430078

2. 中国地质大学地质调查研究院, 湖北武汉 430074

摘要: 岩溶管道与裂隙介质间的溶质交换是岩溶地下水溶质运移过程中一种常见的现象, 其对岩溶水系统中污染物的运移过程具有关键控制作用. 我国南方岩溶区管道与裂隙介质间的溶质交换在灌入式集中补给条件下十分复杂, 其物理过程刻画与模拟极具挑战. 基于对国内外相关研究成果的归纳整理, 总结分析了溶质交换过程的观测、试验、机理、控制因素和模拟方法, 并指出了当前研究中存在的薄弱环节. 进一步的研究应在结合野外实际条件的基础上, 开展室内非稳定流条件下的溶质交换控制性试验, 分析其影响控制因素, 揭示管道与裂隙介质间溶质交换的物理机制; 深入对溶质交换边界条件的刻画, 建立耦合溶质交换过程的溶质运移数学模型, 并利用野外场地尺度的人工示踪试验进行验证.

关键词: 岩溶管道; 裂隙; 溶质交换; 溶质运移; 研究进展; 水文地质; 环境地质.

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Review of Solute Exchange between Karst Conduit and Matrix

Luo Mingming¹, Chen Jing¹, Ji Huaisong¹, Wan Li¹, Li Chenggen¹, Zhou Hong²

1. School of Environmental Studies, China University of Geosciences, Wuhan 430078, China

2. Institute of Geological Survey, China University of Geosciences, Wuhan 430074, China

Abstract: The solute exchange between karst conduit and matrix is a common phenomenon during solute transport in karst groundwater, which has a key control effect on pollutant transport in karst water system. The solute exchange between conduit and matrix becomes very complicated under the concentrated recharge condition, which is a challenge to characterize the physical process and simulation. Based on literature in related fields, in this paper it summarizes the observation, test methods, mechanism, control factors, as well as current simulation methods of solute exchange between karst conduit and matrix, and points out the existing problems in the researches. The solute exchange control experiments under the conditions of unsteady flow should be conducted by indoor conduit-matrix physical models for further researches, which will help analyze its influencing control factors and reveal the physical mechanism of solute exchange between the conduit and matrix. The mathematical model of solute transport coupled solute exchange process should be established by describing solute exchange boundary conditions, which needs to be verified by field tracer tests.

Key words: karst conduit; matrix; solute exchange; solute transport; research progress; hydrogeology; environmental geology.

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作者简介: 罗明明 (1989-), 男, 副教授, 博士生导师, 主要从事水文地质环境地质方面的教学与科研工作. ORCID: 0000-0002-5192-6466.

E-mail: luomingming@cug.edu.cn

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0 引言

在我国南方裸露型岩溶区,由于复杂岩溶地质结构导致的结构性缺水,以及岩溶地下水极高的易污性导致的水质型缺水,正严重威胁着当地的水资源开发利用与生态安全(石亮星等,2022),当地经济社会发展与生态环境健康发展对清洁水资源供给和岩溶水污染防治提出了空前紧迫的需求(韩行瑞,2015;袁道先,2015;曹建华等,2017;Goldscheider *et al.*, 2020;江成鑫等,2021).在岩溶水补给过程中,来自地表的各种水源常携带岩溶洼地的污染物通过落水洞呈集中灌入式补给进入地下河系统,污染物在岩溶管道(conduit)和裂隙介质(matrix)中的迁移规律直接控制着地下河系统的污染过程,影响着水质的变化(Ghasemizadeh *et al.*, 2012; Luo *et al.*, 2016a; 陈静等,2019;邹胜章等,2019;Yang *et al.*, 2020).

污染物在地下河系统中的运移过程十分复杂,往往需要经历岩溶管道和裂隙等多重含水介质(李严等,2021),其中污染物在岩溶管道与裂隙介质间的交换是一种十分普遍的现象(Bauer *et al.*, 2003; Binet *et al.*, 2017; Cholet *et al.*, 2017).在强降雨补给条件下,岩溶管道内的水位迅速上升,水头差驱使管道内的水流和溶质进入到与管道连通的裂隙介质中;降雨结束以后,水力梯度发生反转,管道成为周围裂隙的排水通道,裂隙中携带溶质的水流则以较低的流速缓慢释放进入管道中(Bailly-Comte *et al.*, 2010; Zhang *et al.*, 2020).一次降雨集中补给过程就好比一次脉冲输入,管道与裂隙介质间的水力梯度在脉冲输入前后发生转变,水流与溶质在管道与裂隙介质间经历了一个交换过程(Martin and Dean, 2001; Schmidt *et al.*, 2014).这个交换过程增加了污染物在岩溶水系统中的滞留时间,影响着污染物的物理-化学-生物反应变化、污染物浓度衰减过程与延迟释放、污染物穿透曲线拖尾或多峰形态等,对污染物在岩溶水系统中的迁移过程起到了十分重要的控制作用(Li *et al.*, 2008; 赵小二,2018; Chen *et al.*, 2020).

国内外学者对于管道-裂隙间水流与溶质交换的研究十分关注(Mohammadi *et al.*, 2021),但基本上都考虑为稳定流试验条件,且多聚焦于水流的运动和交换过程.而在我国南方岩溶区的实际补给过程中,落水洞向地下河的补给不是一个持续而恒定的过程,往往是在降雨后形成一个脉冲式的集中补

给过程(Luo *et al.*, 2018a),表现为一种非稳定流条件下的水文响应过程.因此,对于不同补给条件和不同流态下的溶质交换,其交换过程与机理、观测与试验、模拟技术等还需要进行系统的梳理,为后续溶质交换过程与机理的研究理清思路.

综上所述,岩溶管道与裂隙介质间的溶质交换过程对岩溶水系统中溶质的迁移过程有重要影响,溶质交换过程的刻画与机理的研究对岩溶地下水污染的防控与修复、溶质交换数值模型的开发与优化、水资源开发与利用等具有重要意义,对深化岩溶地下水动力学和溶质运移机理的基础理论研究具有积极推动作用.

1 岩溶管道与裂隙介质间溶质交换过程

袁道先等(2016)将全球岩溶区划为冰川岩溶区、亚欧板块岩溶区、北美板块岩溶区以及冈瓦纳大陆岩溶区四个大区.中国位于亚欧板块岩溶区,其岩溶基本类型又可划分为热带及亚热带岩溶、干旱和半干旱区岩溶、温带湿润区岩溶、高原高山岩溶及其他非地带性岩溶(包括热水岩溶、蒸发岩盐岩溶、滨海岩溶、古岩溶).管道与裂隙介质间溶质交换现象主要发生于岩溶管道与裂隙并存的岩溶水系统中,本文提出的岩溶管道与裂隙介质间的溶质交换过程主要适用于岩溶较为发育的区域,例如我国南方岩溶区和部分滨海岩溶区.

在我国南方岩溶区,岩溶含水介质具有高度的非均质性,常常是洞穴、管道、裂隙、孔隙等多重含水介质并存,不同大小空隙中的地下水运动并不同步(罗明明等,2015;Luo *et al.*, 2018b).岩溶含水层中的空隙主要包括原生孔隙(rock matrix)、次生裂隙(fractures and joints)以及溶蚀管道和洞穴(solution cavities and conduits)三部分.通常情况下将溶蚀管道和洞穴中的水视为管道流,而将原生孔隙和次生裂隙视为裂隙流.在小于1 mm孔径的孔隙中,水流往往表现为层流(Hubbert, 1940),而在岩溶含水层的主要通道中,流动通常表现为紊流(Smith *et al.*, 1976).降水时,通过地表的落水洞、溶斗等,岩溶管道迅速大量吸收降水及地表水,水位抬升快,形成水位高脊,在向下游流动的同时还向周围裂隙及孔隙散流(图1);枯水期岩溶管道排水迅速,形成水位凹槽,周围裂隙及孔隙中的水,向管道流汇集(张人权等,2018).在这个管道流与裂隙流交换的过

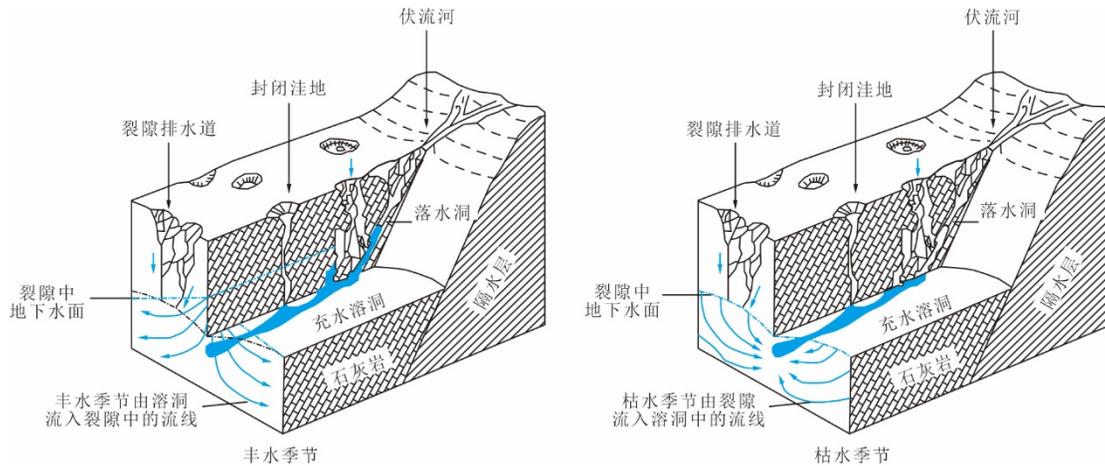


图1 丰水及枯水季节岩溶水的流动关系示意(据张人权等, 2018 修改)

Fig.1 Schematic diagram of karst water flow in wet and dry seasons (modified according to Zhang *et al.*, 2018)

程中,管道流和裂隙流均呈现出非稳定流状态,并伴随着管道流与裂隙流中溶质的交换.

岩溶水系统排泄出口溶质浓度历时曲线(穿透曲线)是溶质在管道-裂隙介质(conduit-matrix)系统中运移过程的综合反映,通过野外人工地下水示踪试验获得的穿透曲线形状通常呈偏态分布,穿透曲线的拖尾现象十分常见,甚至出现多峰现象.溶质的吸附解吸、管道与裂隙的溶质交换、溶质与滞留区水体的混合、溶质在管道流中的稀释、分支管道的溶质分流与叠加等过程均可以造成溶质穿透曲线的拖尾或多峰现象(Field and Leij, 2012; 赵小二, 2018).由于我国南方岩溶区管道与裂隙介质并存,加之季风气候区的集中降雨事件频繁,管道与裂隙介质间的水力关系经常在降雨前后发生转换,因此管道与裂隙之间时常发生水流和溶质的交换,这是导致溶质穿透曲线拖尾效应的重要原因之一(Zhang *et al.*, 2020).

2 溶质交换过程的观测及试验

关于管道与裂隙介质间水流与溶质交换过程的研究,前人的研究从野外场地和室内物理模型两个尺度进行了探索.

(1)野外场地尺度.在野外场地尺度的案例研究中,前人已经通过水文观测、示踪试验等方法观测到了岩溶管道与裂隙介质间的水流和溶质交换现象.水文观测法通过观测岩溶泉的流量、电导率、典型水化学组分等指标来研究岩溶管道与裂隙介质之间的水量交换、压力传导以及溶质交换规律(Bailly-Comte *et al.*, 2010).示踪试验法则更为直

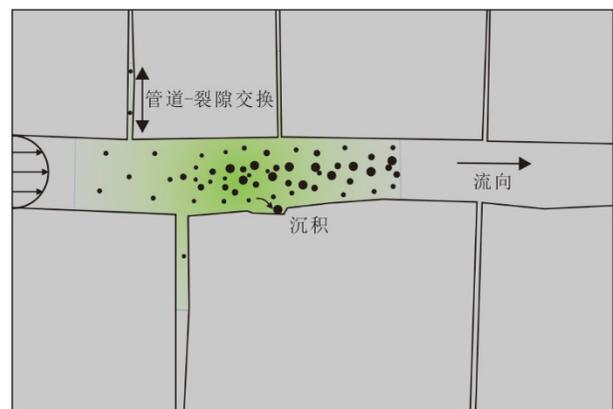


图2 颗粒在管道与裂隙中暂态存储示意

Fig.2 Schematic diagram of particle transient storage between conduit and fissures

据 Goepfert and Goldscheider (2019) 修改.大颗粒主要在管道中运移,具有较高的流速和较低的弥散度,并容易沉积;细小颗粒或溶质(绿色部分)分布于整个系统,可进入裂隙介质,具有较低的流速和较高的弥散度

观,通过对某一具体示踪剂在岩溶含水层中的运移规律来揭示岩溶管道与裂隙介质之间溶质运移和交换过程.水中的天然沉积物、水化学组分和稳定同位素均可以作为示踪剂用于揭示岩溶管道与裂隙介质间的水流交换、混合和暂态存储规律(图2)(Binet *et al.*, 2017; Frank *et al.*, 2019; Goepfert and Goldscheider, 2019).

由于野外场地尺度的管道-裂隙间水流与溶质交换过程研究极度受限于岩溶水系统结构的刻画,观测水头变化和水流交换比溶质交换相对直观和容易,总体在这方面成功开展的场地尺度溶质交换研究案例较少.因此,对于野外实际条件下的溶质交换过程观测亟需加强,但想

找到一个理想的野外观测场地仍然具有难度。

(2)室内物理模型尺度. 由于室内物理模型有条件可控、成本较低等优点,为了进一步探究物理结构和水动力条件对水流运动和溶质运移的影响,前人多使用室内物理模型来开展研究(Zhang *et al.*, 2022).简单化和尺度效应是室内物理模型面临的主要问题.因此,为了将场地尺度条件放大或缩小到实验室尺度,需要保持几何学、运动学及力学三方面的相似度(Mohammadi *et al.*, 2021).

在研究岩溶水流运动或溶质运移规律的室内物理模型中,常见的有砂箱模型(sandbox model)、岩块模型(rockblock model)、管道-裂隙网络模型(pipe/fracture network model)、管道-裂隙耦合模型(pipe and matrix coupling models)(Mohammadi *et al.*, 2021).其中,用于研究管道与裂隙介质间水流或溶质交换最常见的是管道-裂隙耦合模型(图3),这类模型考虑了管道与裂隙之间的水头差和水流交换,且这些模型几乎在装置中都将管道和裂隙两侧设置为水头边界(Li *et al.*, 2008;Faulkner *et al.*, 2009; Gallegos *et al.*, 2013; Mohammadi *et al.*, 2019;赵良杰,2019).例如:Li *et al.*(2008)通过室内垂向砂箱物理模型试验,研究了管道与裂隙介质间溶质的主动与被动交换对穿透曲线拖尾效应的影响.Faulkner *et al.*(2009)以美国佛罗里达岩溶场地为原型,建立室内砂箱物理模型,研究了定水头条件下管道与裂隙间的水量和溶质交换规律.

由于管道-裂隙耦合模型考虑了水流和溶质在两种介质中的流动和交换,同时通过调整实验条件可实现层流和紊流,使得这类模型对于改进岩溶含水层的模拟具有很大潜力.尽管这些模型两侧的水头边界可以调节水头高度,但绝大部分的实验均是在定水头稳定流条件下开展的,对单次补给过程存在水头变化的非稳定流情况未有涉及.

在我国南方岩溶区的野外实际场地条件下,地下河或大型岩溶泉多是以单一出口或泉群的形式向地表排泄.管道与裂隙的水流和溶质交换主要发生在落水洞垂向补给过程中和饱水带水平管道的径流中.此时地下河出口处则一般不存在连续的垂直水头边界来同时控制管道和裂隙介质中的水位,地下河出口往往受岩溶管道出口的排泄标高控制,形成全排型岩溶水系统(罗明明等,2014;Luo *et al.*, 2016b).因此,以我国南方典型岩溶水系统来建立物理模型,出口处则一般不太可能出现裂隙和管

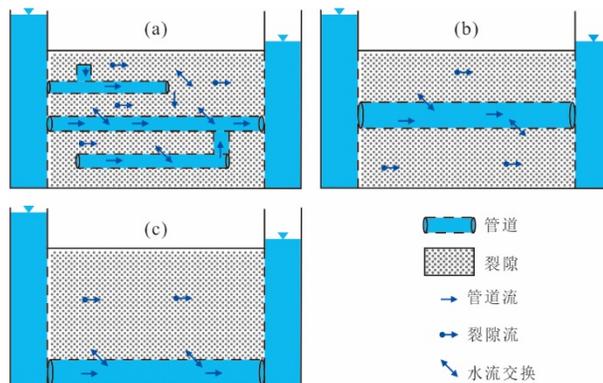


图3 管道-裂隙耦合物理模型结构示意图(据文献Mohammadi *et al.*, 2021修改)

Fig.3 Schematic diagram of different configurations used as pipe and matrix coupling models (modified according to Mohammadi *et al.*, 2021)

a. 多个树杈型分支管道镶嵌于砂箱中,管道四周均可以发生交换;b. 单个管道位于砂箱中部,管道四周均可以发生交换;c. 单个管道位于砂箱底部,只有管道上方可发生交换;管道-裂隙系统的补给和排泄均为定水头边界,两侧水槽与砂箱均有直接水力联系;管道流通常用一个管道或一系列交叉的管道来表示,一般把管道埋置在裂隙介质内部或外部边缘;裂隙介质一般用渗透性相对较低的细砂、玻璃珠、陶瓷土等来代替

道的共同水头边界,前人的管道-裂隙耦合模型则不太适用于模拟我国南方的完整岩溶水系统,而只适用于某一段水平的岩溶管道与裂隙的交换过程刻画.

在考虑完整岩溶水系统的室内建模方面,牛子豪等(2017)以我国西南地区的典型岩溶水系统为原型,研制了管道-裂隙介质物理模型(图4),其设置一侧为水头边界,一侧为管道出口,无水头边界控制,比较符合我国西南岩溶区的实际情况.Wu *et al.*(2019)和 Shu *et al.*(2020)以我国北方济南岩溶大泉为原型,建立室内管道-裂隙物理模型.这些案例多聚焦于岩溶水系统的退水规律和水量交换问题,尚未涉及到溶质运移和交换过程的研究.

相比于溶质交换规律的研究,前人的室内物理模型更多地聚焦于管道结构和溶潭等对溶质运移的影响研究.大量的室内物理模型试验研究表明,多管道和溶潭不仅会造成穿透曲线的拖尾(Wu and Hunkeler, 2013;Zhao *et al.*, 2021),在一定的条件下还会出现双峰现象(Field and Leij, 2012; Mohammadi *et al.*, 2019; Wang *et al.*, 2020).那么,溶质在管道与裂隙交换的过程中除了造成拖尾现象,会不会也有可能出现双峰现象呢?目前这是一个尚未被回答的问题.

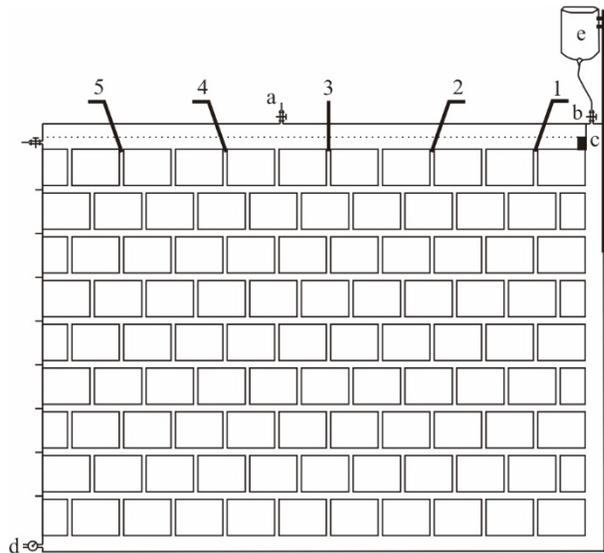


图4 裂隙-管道介质物理模型(据牛子豪等,2017修改)

Fig.4 Schematic diagram showing the physical model of matrix and conduit (modified according to Niu *et al.*, 2017)

a.裂隙分散补给开关;b.管道集中补给开关;c.裂隙网络与管道补给系统之间的挡板;d.流量计;e.示踪剂添加装置;1~5.裂隙入口;裂隙介质用玻璃砖来模拟;裂隙分散补给和管道集中补给为恒定水头,只有底部管道出口可排泄,排泄无恒定水头控制

总体而言,涉及管道-裂隙溶质交换的室内物理模型较为少见,多是以研究水流运动与交换为主,且均是在稳定流条件下开展的室内试验.我国南方岩溶区落水洞接受降雨集中补给的过程中,管道中的水位随着降雨补给过程的结束表现为快速涨落,呈现出脉冲式输入的特点,传统的物理模型不太适用于我国南方岩溶区这种脉冲式集中补给条件下的水流和溶质交换过程刻画.

3 溶质交换机理与控制因素

刻画管道与裂隙介质的水流交换是研究溶质交换的前提.岩溶管道与裂隙间的水流交换主要取决于两种介质间的水头差及界面间的交换能力.在管道-裂隙系统中,出口的流量过程和内部的水头变化受到了管道尺寸、裂隙介质空隙度和水量交换系数等的影响(束龙仓等,2013;孙晨等,2014;Shu *et al.*, 2020;张春艳等,2020),而溶质运移及其交换过程又受到水量和水压变化等因素的控制(腾强等,2014;Mohammadi *et al.*, 2021),水动力条件的增强还会造成出口溶质穿透曲线的拖尾和多峰现象(罗明明,2018;罗明明和季怀松,2022).且管道和裂隙的断面尺寸及形态也会影响到溶质穿透曲

线的形态(Ronayne, 2013;计顺顺等,2017;季怀松等,2020).此外,岩溶管道内水位暴涨暴落的过程中,极易造成管道流呈现明流与满流交替、层流和紊流相互转化的现象(孙欢等,2020),流态的改变也影响着溶质传输与交换过程.总体而言,管道-裂隙的物理结构和水动力条件会显著影响岩溶水系统中的水流运动和溶质迁移过程,进而决定着管道-裂隙间溶质交换的差异.

在不同的水动力条件下,岩溶管道与裂隙介质间常存在水流与溶质的交换,前人通常利用线性方程来定量刻画这种交换过程(式1)(赵良杰,2019):

$$q_{\text{exchange}} = \alpha(h_{\text{matrix}} - h_{\text{conduit}}), \quad (1)$$

式中, q_{exchange} 代表单位面积上管道与裂隙间的水流交换量(L^2T^{-1}); α 代表单位面积上的水流交换系数(LT^{-1}),受裂隙渗透系数、交换表面积、管道水力梯度和管道形态等因素控制; h_{matrix} 代表裂隙介质的水头(L); h_{conduit} 代表管道内的水头(L).

对于岩溶管道的实际补给过程而言,在一次集中降雨补给事件过程前后,管道与裂隙水位均不是恒定的,管道与裂隙水位的变化与水力梯度的反转影响着裂隙的充水和释水过程(Bailly-Comte *et al.*, 2010).无论是裂隙充水,还是释水过程,受管道水位快速上涨和衰退的影响,充水量和释水量的变化均不是线性过程,导致其中携带溶质的交换过程也更为复杂.因此,利用线性方程来刻画非稳定流条件下的水流和溶质交换不再适用.

除管道-裂隙结构和水流特征外,溶质的种类和特性也是影响溶质交换过程的重要因素,保守型和非保守型溶质的运移过程存在显著差别(Luhmann *et al.*, 2012).目前岩溶水系统溶质运移的研究多集中于保守型溶质,其性状稳定、便于观测,只需考虑溶质运移的物理作用.例如,NaCl、胭脂红等多用于室内试验的研究(张雪梅,2019),而荧光素钠、罗丹明、荧光增白剂等有机染料则常用于野外人工示踪试验(Zhang *et al.*, 2020).在实际的岩溶水系统中,氮素、颗粒、有机物等非稳定的溶质或污染物是大量存在的(陈余道等,2014;Goepfert and Goldscheider, 2019;Chen *et al.*, 2020),涉及到化学或生物作用的岩溶管道-裂隙介质间的溶质交换过程与机理研究目前也较为缺乏.

4 溶质交换过程模拟

岩溶管道溶质运移模拟中常用的模型包

括概念模型和数值模型。

(1) 概念模型. 概念模型常用于拟合解释溶质穿透曲线形态, 被广泛地应用于岩溶管道溶质运移的研究. 一些常用的概念模型包括一维或改进的对流-弥散模型、裂隙扩散模型、两区非平衡模型(two-region nonequilibrium model) (Toride *et al.*, 1993; Field and Pinsky, 2000)、暂态存储模型(transient storage model) (Bencala, 1983; Morales *et al.*, 2010; Dewaide *et al.*, 2016)、连续时间随机游走模型(continuous time random walk model) (Berkowitz *et al.*, 2006, 2016; Göppert and Goldscheider, 2008; Cortis and Berkowitz, 2010)等. 对流-弥散方程是最经典的溶质运移方程, 在相对简单的岩溶水系统的水流和溶质运移模拟过程中能取得较好的效果(Cholet *et al.*, 2017). 针对复杂岩溶水系统中的长拖尾型穿透曲线, 两区非平衡模型、暂态存储模型及连续时间随机游走模型则具有相对更好的拟合效果(郭芳等, 2016; Goeppert *et al.*, 2020; 赵小二等, 2020).

暂态存储模型定义了主通道和存储区, 存储区相对主通道而言被认为是不流动的区域, 其中不包含对流和弥散过程(图5). 方程适用于保守型溶质, 比如示踪剂的运移. 两区模型假设非流动区水体沿着溶质运移路径均匀分布, 流动区和非流动区之间存在溶质交换, 但对流运移过程只在流动区中发生(Field and Pinsky, 2000), 其方程式为:

$$\theta_m \frac{\partial C_1}{\partial t} = \theta_m D_m \frac{\partial^2 C_1}{\partial x^2} - \theta_m v_m \frac{\partial C_1}{\partial x} - \alpha(C_1 - C_2) - (\theta_m \mu_{1,m}) C_2, \quad (2)$$

$$\left(\theta_{im} + \frac{2K_a}{r} \right) \frac{\partial C_2}{\partial t} = \alpha(C_1 - C_2) - \left(\theta_m \mu_{1,m} + \frac{2K_a}{r} \mu_{ad,im} \right) C_2, \quad (3)$$

式中, t 为时间[T]; x 为注入点下游距离[L]; θ_m 、 θ_{im} 为流动区域和非流动区域的有效孔隙度[无量纲]; C_1 和 C_2 为流动区和非流动区溶质浓度[M/L³]; α 为传质系数[T⁻¹]; D_m 为流动区域弥散系数[L²/T]; V_m 为流动区域平均流速[L/T]; $\mu_{1,m}$ 、 $\mu_{1,im}$ 为流动区域和非流动区域液相溶质的一阶衰减系数[T⁻¹]; $\mu_{ad,im}$ 为固体吸附相溶质的一阶衰减系数[T⁻¹]; K_a 为单位面积固体吸附的溶质质量与溶液中浓度的比值[L]; r 为岩溶管道截面半径[L].

这些模型虽然能对示踪剂穿透曲线产生良好的拟合效果, 但不能把管道裂隙结构参数和溶质交

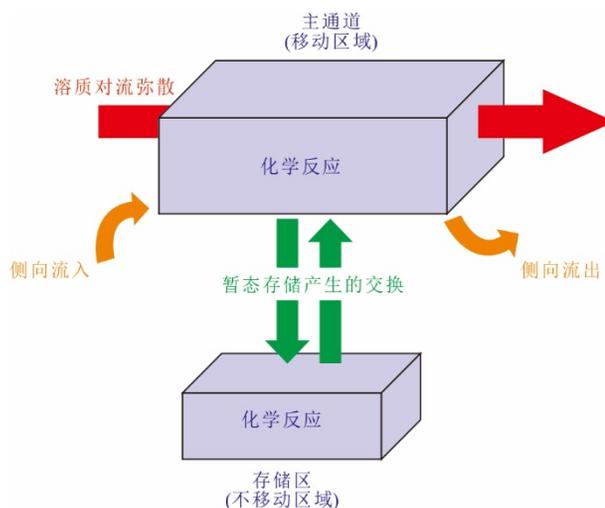


图5 暂态存储模型的主要功能原理(据 Dewaide *et al.*, 2016 修改)

Fig.5 Main functioning principles in transient storage model (OTIS) (modified according to Dewaide *et al.*, 2016)
溶质运移主要在主通道进行, 同时与存储区发生交换

换系数等与岩溶水系统实际物理结构联系起来, 模型参数的物理意义不够明确, 很少分析模型参数与水动力条件、管道裂隙结构之间的关系, 模型得到的参数也很难推广应用到其他岩溶水系统.

(2) 数值模型. 前人也尝试用数值模型来模拟管道与裂隙间的水流与溶质交换, 常用的包括基于 Modflow-CFP (Reimann *et al.*, 2011; Mohammadi *et al.*, 2018) 和 COMSOL (Wu and Hunkeler, 2013) 等进行的水流及溶质交换模拟. 其中 MODFLOW-CFP 在管道-裂隙介质水流交换的室内试验模拟中取得了较好的效果 (Gallegos *et al.*, 2013; Shu *et al.*, 2020). 在管道-裂隙水流交换的基础上耦合溶质运移模拟时, 前人使用了经典的 MT3D 溶质运移模型. CFP 和 MT3D 的耦合模型已被多次成功应用于地下河及岩溶管道系统中的溶质运移模拟 (Xu *et al.*, 2015; 杨杨等, 2019).

CFP 模型考虑了岩溶管道的层流和紊流状态, 耦合至等效介质的水流模型中, 但没有考虑管道内部的水动力过程变化, 且管道与裂隙介质间的水流交换采用线性方程, 这难以符合我国南方脉冲式补给条件下的水流和溶质交换规律.

在管道流和裂隙流等多相流耦合刻画中, 前人常用 Stokes 方程来刻画管道流, 用 Darcy 方程来刻画裂隙渗流, 用 Beavers-Joseph 边界条件来刻画管道与裂隙介质的水流交换 (Faulkner *et al.*, 2009). 在管道流与裂隙流耦合时, 由于 Stokes 和 Darcy 两

个方程的微分阶次不同,需要在交界面处引入合适的界面条件,Beavers-Joseph 速度滑移条件是目前应用最多的界面交换条件(式 4),尤其是应用在碳酸盐岩缝洞型油气藏的研究方面(黄佩奇和陈金如,2011;黄朝琴等,2014):

$$\begin{cases} \mathbf{u}_s \cdot \mathbf{n} = \mathbf{u}_d \cdot \mathbf{n}, \\ p_s - \mathbf{n}^T \cdot \boldsymbol{\tau} \cdot \mathbf{n} = p_d, \\ -\mathbf{n}^T \cdot \boldsymbol{\tau} \cdot \mathbf{t} = \frac{\mu \alpha}{\sqrt{\mathbf{t}^T \cdot \mathbf{K} \cdot \mathbf{t}}} (\mathbf{u}_s - \mathbf{u}_d) \cdot \mathbf{t}, \end{cases} \quad (4)$$

式中, \mathbf{n} 为交界面的单位法向量; \mathbf{t} 为其单位切向量; \mathbf{u} , p , $\boldsymbol{\tau}$ 分别代表速度向量、压力和切应力张量; μ , \mathbf{K} , α 分别为流体黏度、多孔介质渗透率张量和速度滑移系数;下标 s 和 d 分别代表 Stokes 流和 Darcy 流. 第一个条件为法向速度连续条件;第二个条件为法向应力连续条件;第三个条件则表示管道侧的切向应力与界面处流速过渡的关系(Beavers and Joseph, 1967).

大量的数值模型案例多聚焦于管道-裂隙介质间的水流交换,成功模拟溶质交换的案例较少见. 针对我国南方岩溶区接受降雨补给后呈现出的脉冲式输入特点,还需要不断去探索这种复杂岩溶结构和水动力条件下的考虑溶质交换过程的溶质运移模拟方法.

5 结论与展望

从前文的梳理与分析可知,前人的研究中已经观测到岩溶管道与裂隙介质的溶质交换现象,并对溶质交换过程和模拟做了一定探索,这是引起溶质穿透曲线拖尾或多峰现象的重要原因. 但管道与裂隙介质间溶质交换过程和机理仍比较模糊,尤其是应用到模型中时,多假设为线性的交换过程,这难以刻画野外实际岩溶水系统中水头发生变化的补给条件.

在野外的实际补给过程中,落水洞的补给不是一个持续而恒定的过程,往往是在雨后形成一个脉冲式的集中补给过程,因此,管道与裂隙水流不是稳定流条件. 而传统的室内物理模型试验中,基本上都考虑为稳定流试验条件,且多聚焦于水流的交换,目前还未见到非稳定流条件下的溶质交换试验研究. 前人基于稳定流概化的物理模型与刻画的交换机制不再适用于我国南方岩溶区脉冲式补给条件下的溶质交换过程,亟需对这种非稳定流条件下的溶质交换过程与机理开展研究.

为进一步推进岩溶管道与裂隙间溶质交换过程研究,丰富我国南方岩溶地下水溶质运移机理的理论研究体系,针对目前研究中存在的问题,我们提出以下几点研究建议:

(1) 进一步结合我国南方岩溶区野外的实际条件,考虑脉冲式的落水洞集中补给过程,选取水文地质条件比较清晰且易于概化的场地,进行不同降雨条件下的示踪试验. 结合水文过程监测对管道-裂隙介质间的水流与溶质交换过程与交换规律进行对比分析.

(2) 通过概化符合实际条件的水文地质概念模型,建立室内物理模型. 根据控制单一变量原则,展开改变补给水动力条件和管道-裂隙结构等条件的控制性室内试验,以揭示管道-裂隙结构和水动力条件对溶质交换过程的控制机理. 综合对比稳定流和非稳定流条件下溶质迁移过程的差异性,量化变化水头对溶质迁移和交换过程的控制作用.

(3) 进一步探索管道与裂隙介质间水流与溶质交换数学方程,深入对管道-裂隙介质交换边界条件的刻画,建立耦合溶质交换过程的岩溶地下水溶质运移数学模型,实现溶质运移穿透曲线过程的模拟与预测. 考虑室内物理模型与野外场地之间的尺度效应,评估室内试验获取的物理机制和数学模型在野外场地条件下的适用性,探索野外示踪穿透曲线或污染物运移曲线的模拟.

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